The Thesis Committee for Daniel Silva da Silva
Certifies that this is the approved version of the following Thesis:

Farmland expansion and temperature fluctuations in dry areas of the Cerrado biome

APPROVED BY
SUPERVISING COMMITTEE:

Eugenio Y. Arima, Supervisor

Kenneth R. Young, Co-supervisor

Timothy Beach

Farmland expansion and temperature fluctuations in dry areas of the Cerrado biome

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Daniel Silva da Silva

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Dedication

I dedicate this work to my grandfather, who from an early age planted an interest about the history of the occupation of the Brazilian hinterland in the 20th century, and Theo, to who I intend to pass along curiosity.

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Abstract

Farmland expansion and temperature fluctuations in dry areas of the Cerrado biome

Daniel Silva da Silva, M.A.
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Supervisor: Eugenio Y. Arima, Co-Supervisor: Kenneth R. Young

Brazil is one of the largest suppliers of commodities in the world, partly due to the agricultural expansion in the Brazilian savannas (also known as Cerrado) that began in the 1970s, made possible by the green revolution. However, as areas with better soil and climate for agriculture become scarce, farmers have been advancing to the ecotone between the savanna and a semi-arid steppe, where precipitation is less reliable for rainfed agriculture. Therefore, as climate change projections of higher temperatures and lower precipitation in the region come to fruition, the expected financial gains become increasingly unrealistic for the coming decades if breakthroughs in adaptation do not occur. For instance, droughts in 2015/2016 reduced 33% of average productivity in the Cerrado biome and mainly in the Matopiba, a recent agricultural frontier within the Cerrado. The overall goal of this thesis is to investigate the implications of occupying areas of marginal rainfall in the Cerrado due to the dry conditions, which are likely to become more so in the future. First, I estimated the effect of temperature increases on soybean yields from 1980 to 2016 and studied farmer's response to weather fluctuations. I chose soybeans because this is the region’s main crop. My panel data analysis estimated a reduction of 4-17% in soybean yield for each 1°C increase in temperature. According to interviewed farmers, the consequences of the drought in 2015/2016 include land concentration and increased indebtedness. Second, I modeled the future farmland expansion and how that matches with future climate change predictions (2016-2046). According to my estimates, at least 60 thousand km^2 of cropland and 138 thousand km^2 of pastures will be created in places with projected higher annual temperatures. Finally, I discuss the agri-environmental policies that create incentives to push and pull farmland expansion in the Cerrado. Without proper technical-scientific assessment and land management policies, the Matopiba region in the Cerrado may become the Brazilian version of the United States' Dust Bowl, with prolonged periods of inadequate rainfall for soybean production, and lead to financial hardship.

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Chapter 1: Overview

INTRODUCTION

Since 1970 Brazil has emerged as an agricultural powerhouse, partially due to the farmland expansion in its savannas (also known as Cerrado), made possible by the green revolution (Brum et al., 1988). From 1985 to 2019, approximately 30 million hectares of new agricultural areas have been created by converting native vegetation (Souza et al., 2020). Consequently, nowadays the Cerrado is a hotspot for environmental conservation (Myers et al., 2000; Mittermeier et al., 2011) and the fastest growing agricultural region in the world (Graesser et al., 2015). The recent agricultural expansion in the Cerrado occurred mainly for soybean farming, which accounts for 50% of the total planted area in 2018 (IBGE 2018a). Although commitments were made to reduce land clearing, the Brazilian Ministry of Agriculture projects an increase in beef and grain production of ~4% and ~3% per year, respectively, through expansion into new areas and intensification of already cleared areas (Brasil, 2017). However, as areas with better soil for agriculture become scarce, farmers advance to the ecotone between the savanna and the caatinga, a semi-arid environment where adequate precipitation is less reliable. Farmland expansion in these cheaper marginal lands exposes farmers to rainfall shortage and periodic productivity losses (Brito et al., 2018). Thus, the overall goal of this thesis is to investigate the implications of occupying marginal areas in the Cerrado, where rainfall often falls short today and models indicate even dryer future climatic conditions.

This thesis is organized in two building blocks: the assessment of the effect of temperature increases on soybean yield (the major crop in the Cerrado) since 1980, and farmer’s response to weather fluctuations (Chapter 2); and modeling of future farmland expansion and how that matches with future climate change predictions (Chapter 3).

Although connected in the same narrative about the Cerrado, chapters 2 and 3 are conceived as independent pieces, with their own methods, results, and discussion. After providing a background on the farmland expansion in the study area (Chapter 1), I investigate the effect of temperature and precipitation variation across time and space on soybean yields (Chapter 2) and I compare the results with farmers' perceptions of regional weather fluctuations and adaptation strategies. The analysis of crop-weather relationship is multiscalar and partly based on a survey conducted with 90 farmers in the recent agricultural frontier of Matopiba region, in the ecotone between Cerrado and a semi-arid biome (Caatinga). After analyzing the recent land change and relationship between climate and soy yield, Chapter 3 presents a land change model and compares how future climatic conditions differ from the current climate in these new agricultural areas vulnerable to droughts. Finally, Chapter 4 concludes by highlighting the main results and discussions in the previous chapters, then indicates future research topics based on the results of this thesis.

BACKGROUND

Green revolution and environmental issues

Food supply and affordability has always been the focus of government food policies, and in the 1960s, several technological innovations in agriculture allowed an exponential increase in the productivity of staple foods (e.g., wheat, rice, soy). These innovations also included the development of pesticides, herbicides, chemical fertilizers, and new ways to correct soil acidity and the use of agricultural machinery (Pingali, 2012). The adoption of these technologies was accelerated by public investments in research and international transfer of adaptable seed varieties to marginal lands in under development countries (Pingali, 2012). These transformations in the agricultural sector became known as the Green Revolution (GR), a cornerstone for the modern agriculture and the accelerated growth of agricultural outputs.

In the early years, the GR was associated with increased food supply and affordability due to decreasing production costs that reduced prices for consumers (Everson & Gollin, 2003; Pingali, 2012). For this reason, some authors consider the green revolution innovations as part of a success model of economic growth, also known as “structural transformation,” which aims at intensive use of capital in large areas of croplands, international trade, rural migration to urban areas, and strong industrial sector leading the economy with investments in the modernization of the agricultural sector (Timmer, 2015). Since the early 2000s, new technological breakthroughs have been widely applied in the agriculture areas of developing countries, such as precision agriculture, the use of geographic information systems in crop planning, and genetically modified organisms (GMOs). This new wave of agricultural technologies expands the range of the original improved seed varieties (Pingali, 2012). Although the benefits to food security are obvious, the lessons from the latest green revolution raise concerns about the consequences for reducing social inequalities, environmental impact, and climate adaptation in marginal environments (Pingali, 2012; Tscharntke et al., 2012).

Despite the increasing agricultural improvements over recent decades to meet the food demand, the farmland expansion under the Green Revolution’s techniques has unintended consequences in soil degradation, biodiversity losses, and greenhouse gases emission (Pingali, 2012). The impacts of modern agriculture also include reduced groundwater, decreased crop diversity and resistance to invasive weed species with consequent dependence on pesticides (Tscharntke et al., 2005). In the farms, these environmental impacts have increased the dependency on capital availability (e.g., for irrigation in marginal lands and pesticides in the major crops) and vulnerability to weather fluctuations and economic shocks. These environmental impacts are widely recognized as a potential threat to the long-term resiliency of socio-environmental systems; particularly in the expected scenario of climate change and increasing demand for ecosystem services, such as water supply (Allan, 2004; Coe et al., 2011; Latrubesse et al., 2019).

The importance of Cerrado biome

The Cerrado is important for food production but more so for conservation of global biodiversity. This biome has the richest flora among the world's savannas (~10,000 species of plants) and 2,135 vertebrate species, with 39% of endemism for both (Mittermeier et al., 2011). It is estimated that the Cerrado has 677 flora species threatened with extinction (Brasil, 2014). Moreover, this region contains the headwaters of South America's major river basins (Paraná-Paraguay, Araguaia-Tocantins, and São Francisco), but the land clearing has affected the hidro-geomorphology and water security in this ecosystem (Latrubesse et al, 2019). Although the Cerrado is adapted to wildfires, the frequent burning of pastures has resulted in major problems with disturbance on habitats and carbon cycle, leaching, and soil erosion (Klink & Machado, 2005).

Since the 1960s, succeeding Brazilian governments oriented their public policies to food sovereignty based on a structural transformation approach: high investments in research and infrastructure, rural credit and other incentives to modern large-scale agriculture aiming the international trade. Consequently, nowadays the Cerrado biome is the fastest growing agricultural region in the world (Graesser et al., 2015), the world's leading soy producer and exporter, and the largest hotspot for biodiversity conservation in the western hemisphere (Myers et al., 2000; Mittermeier et al., 2011). By 2019, the Cerrado biome lost ~44% of its native vegetation to agricultural areas (Souza et al., 2020), or 86 million hectares. The annual land clearing rates are higher than in the Amazon rainforest, but with much less conservation effort (only 8% of the Cerrado cover is protected by law). Most of the remaining native vegetation is fragmented, with reduced effectiveness to biodiversity conservation and ecosystem services.

STUDY AREA

The research focused on the Cerrado biome, the second largest biome in South America after the Amazon (Figure 1.1). The Cerrado is characterized by pronounced dry and wet seasons. Rainfed agriculture is practiced from September to April, and this rainy period concentrates 80% of the total annual precipitation that ranges from 900 mm at the semi-arid caatinga ecotone to 2000 mm in the Amazonian ecotone (Embrapa, 2020). The soils are well developed but fertility is low, and acidity is high with pH ranging from 4.3 to 5.5 (Yamada, 2006). Despite the agronomic limitations, since 1960 this biome underwent an intensive occupation process, and now accounts for more than half of the grain production in Brazil (Brum, 1988; Graesser et al., 2015; IBGE, 2018a).

Two factors explain the modernization and expansion of Brazilian agriculture: the 1960/1970s public policies aimed at developing the country and the development of technologies for managing soil fertilization in the tropics that allowed soy expansion in the savannas of the Cerrado biome. The main technologies that enable annual crops in the Cerrado included better-adapted seeds (more recently developed seeds include genetic modified organisms), combined with acidity correction using limestone, and chemical fertilizers such as phosphorus, potassium, and nitrogen (Embrapa, 2020). Management techniques such as minimum tillage were also developed and are now widely adopted by farmers. As a result, crop productivity increased from 43 to 2,900 kg/ha since 1980 (IBGE, 2018a). According to Brum (1987), the introduction of soybean cultivation is the symbol of the agricultural green revolution in the Cerrado since the 1970s. Brum (1987) maintains the soybean expansion represents the power of capital in ‘creating the natural conditions’ to farming, and it launched Brazil as a major supplier in the international food market. In order to advance these technologies, the government invested heavily in agricultural research for tropical climate, through the creation of the Brazilian Agricultural Research Company (Embrapa, in Portuguese acronym), and several other policies to occupy the hinterlands of Brazil.

The modernization of the Brazilian agriculture and occupation of Cerrado biome was encouraged by the federal government since the1960s with the goal of increasing food production, meeting domestic demand, and achieving a commercial trade balance surplus (Brum, 1987). The move of the capital from Rio de Janeiro to Brasilia in 1960 was the first political effort to integrate and develop the different regions of Brazil. The capital change to a central region also moved financial flows and created political conditions for infrastructure expansion in the Cerrado. In the mid-1970s, the government created the Cerrados Development Program (Polocentro, in Portuguese acronym), which oversaw investments in agricultural research and infrastructure (e.g., roads, silos) to the country's Midwest region (Embrapa, 2020). It is worth mentioning that until then the Cerrado was considered a wasteland unsuitable for agriculture, and that is why the creation of Embrapa was crucial for the development of technologies adapted to the tropical climate. The National System for Rural Credit (SNCR in the Portuguese acronym), created in 1965, facilitated the purchase of machinery and inputs (fertilizer, limestone), with the goal of providing food security and Brazil's independence from international agricultural products (Brum, 2012). Finally, the Japanese-Brazilian Cooperation Program for the Development of the Cerrados (Prodecer, in Portuguese acronym) played an important role in agricultural development from the 1970s to the 1990s, through governmental financial resources (i.e., Japan International Cooperation Agency) and through private banks (i.e., Long Term Credit Bank) (Yoshii, Camargo, Orioli, 2000).

With most of the Cerrados closer to São Paulo occupied by the early 1990s, farmland expansion advanced to the transition areas between Cerrado and Amazonia, such as Mato Grosso state and more recently to the Matopiba (Figure 1.1). The Matopiba region is a transition area between the Cerrado and the Amazon to the west the Caatinga to the east, encompassing 73 million hectares. Since 2005, the Cerrado vegetation has been highly cleared, mainly for soy production. At the border with the Caatinga semi-arid biome, the main advantage for agriculture is the proximity to ports for export commodities and the good road network. Due to a relatively long dry period that extends from 4 to 6 months, more than 180,450 hectares are now irrigated in the Matopiba region, mostly by center pivot systems that rely both on surface and groundwater (ANA & Embrapa, 2019). Irrigation is part of the green revolution package and allows for up to three harvests per year. This dependence on irrigation is often associated with local conflicts and water shortages (Maneta et al., 2009; Pousa et al., 2019). Because agriculture in this region has periodic drought stress related to the El Niño Southern Oscillation, farmers, governments, and related stakeholders must consider adaptations to climate change since models predict higher temperatures and reduced rainfall amounts (Cunha et al., 2019; IPCC, 2014; Pires et al., 2016). The socioeconomic consequences of future climate are many and, without government policies, may include for example land concentration and higher indebtedness due to lost production resulting from extreme weather events.

In May 2015, the Brazilian government enacted a decree to steer development policies in the Matopiba region. This plan, called Agrarian Development Plan (PDA in Portuguese acronym) and led by the Ministry of Agriculture and Embrapa's Territorial Intelligence Group (Embrapa/GITE) officially defined the geographic boundaries of the

Matopiba territory and highlighted agribusiness as the main driver of development for the region. The objective of the PDA was to promote infrastructure investments to facilitate transport of agricultural goods, to encourage the development of technologies inherent to agribusiness, and to increase income through the technical qualification of farmers and workers (BRASIL 2015). Although the decree defining the institutional role for the PDA was revoked in 2020, studies conducted under the purview of the program (Embrapa/GITE 2014a, 2014b, 2014c) were optimistic with respect to the socio-environmental conditions of the region for agricultural development, which instigated the recent rush to invest in the area.

The expectations of financial gains in these new agricultural frontiers can be seen in the spatial distribution of land prices (Figure 1.1). In general, land prices are higher in the south/southeast Brazil in São Paulo state and decline in concentric rings from this industrial and agricultural core up to the middle of the Cerrado, where this pattern breaks apart and two regions show higher land prices than neighboring regions: in parts of the Matopiba region and the soy areas in the state of Mato. Walker & Richards (2014) found a similar pattern of land price allocation in Brazil, where declining market access due to distance and freight costs reduces land prices and incentives for land use change. The modeling effort (Chapter 3) seeks to capture these expectations of gain on land use change, while Chapter 2 estimate the effects of higher temperatures in soy productivity. The results and discussion of the next chapters inform about future climate conditions and the risks of occupation marginal areas. I assume in my analyses that the political-economic processes and motivations of farmland expansion in the Cerrado will continue for the next two decades. Therefore, it is worth assessing whether this continuous expansion over marginal lands can lead to a scenario of increased risk for crops.

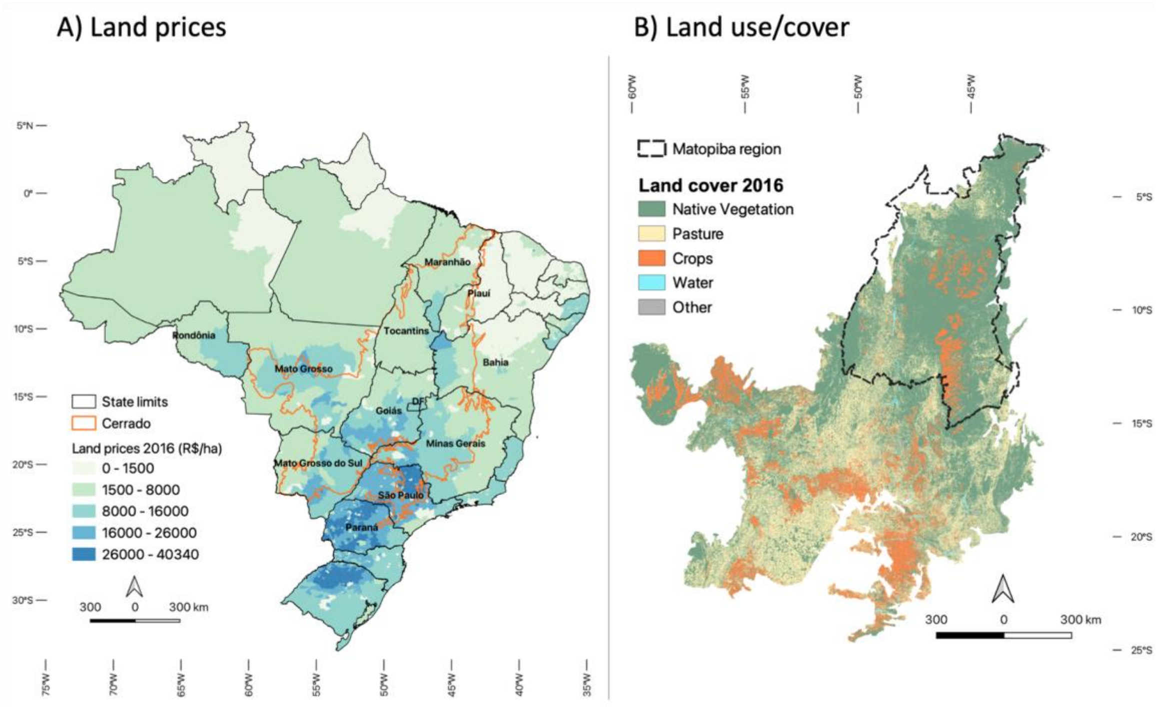

Figure 1.1: (A) Average land prices (BRL/hectare) weighted by cropland and pastureland at municipal level in Brazil, 2016; and (B) land cover in Cerrado, 2016. Source: FNP (2018), Mapbiomas (Souza et al., 2020).

Chapter 2: Temperature effect on Brazilian soybean yields, and farmer's response

The farmland expansion over marginal lands in the Cerrado, exposed farmers to increasing risks (Collins et al., 2013; Brito et al., 2018) due to agribusiness' large capital investments in areas vulnerable to droughts. As the projections of higher temperatures in the Cerrado come to fruition (IPCC, 2020), the expected financial gains become unrealistic for the coming decades. For example, El Niño is correlated with a shortened rainfall in the Amazon and Cerrado biomes (Pires et al, 2016) and resulting crop losses (Anderson et al, 2017). However, stakeholders frequently underestimate long-term climate variability, possibly because they perceive crops yields and adaptation to weather fluctuations only within a short-term horizon (Howden et al., 2007; Butzer & Endfield, 2012). Hence, agricultural adaptation still needs to be further studied, particularly in contextual approaches at the regional scale (Challinor et al., 2014; Denevan, 1983). The Cerrado is an ideal place to investigate the potential impacts of temperature and precipitation on capital-intensive agriculture. Although the Cerrado is a region with water and soil restrictions, there is increasing agricultural expansion due to private investments, governmental support, and international traders (Pires, 2020).

In this chapter, I investigate the effect of temperature and precipitation variation across time and space on yields, and I compare the results with farmers' perceptions of regional weather fluctuations and crops adaptation strategies to temperature and rainfall pattern changes. The analysis presented here is multiscalar and uses different datasets at the municipal level and farm level. At the level of Cerrado municipalities, I investigate the relationship between soy productivity and climate variables (temperature and precipitation) from 1980 to 2018, which might indicate how future climate change may impact agricultural productivity in this area. At the farm-level, I use data from a survey conducted in 2017 with 90 soy farms in the Matopiba region. Two questions drive the analytical framework: (1) Have higher temperatures and lower precipitation regimes affected agricultural productivity in the Cerrado? and (2) Are farmers' perceptions of weather fluctuations and their response (i.e., agricultural practices to mitigate the droughts impact) consistent with the effects of increasing temperature and precipitation changes? My hypotheses are: (i) higher temperatures and lower precipitation are associated with lower agricultural productivity in the Cerrado, (ii) farmers have an unrealistic perception of adaptation, partly because agricultural technologies and public policies provide short-term financial relief. My hypotheses are supported by the studies on crop-climate relationship (Ortiz-Bobea et al., 2020; Zhao et al., 2017; Burke et al., 2015), and the economic history of the Cerrado conquest (Brum, 1988; Pires, 2020).

METHODS

The research uses a multi-scale approach, comparing Cerrado municipal-level data with farm-level data in Matopiba region. The Matopiba (acronym for the states of Maranhão, Tocantins, Piauí and Bahia) is the portion of Cerrado with highest conversion rates of native vegetation to farmland expansion since 2005. To study how the climate dynamics affects productivity and what are the farmers' responses to weather extreme events, I combined statistical analyses and interviews with stakeholders into two building blocks: (1) panel data analyses of soy productivity (kg/ha) on climate variables (temperature and precipitation) from 1980 to 2018, in Cerrado municipalities; and (2) data analysis of 90 interviews with farmers in the Matopiba region, on agricultural practices, economic performance, and perception about changes in temperature and precipitation. Econometrics and statistical analysis were performed using R software package, while the spatial dataset was gathered within the Google Earth Engine platform and analyzed in ArcGIS software.

Data

Climate variables and yield by municipality

The climatic data were obtained through the Google Earth Engine (GEE). The platform houses temperature and precipitation data from Copernicus Climate Change Service (2017). The original temperature data are in Kelvin (air temperature at 2m height, converted to annual average Celsius), and the total annual precipitation data are in millimeters (mm) (Table 2.1). For both annual variables I considered the harvest period for the main crop studied (soybeans), from November to May. No difference in the results were found when I included the variables for the off-season period. Therefore, I show results using only the data for the plant growth period, according to other studies (Schlenker & Roberts 2009). Average values per municipality polygon were calculated by standard zonal statistical functions in ArcGIS and GEE. The municipalities' polygons, soybean productivity (kilogram/hectare), and area planted values were downloaded from the Brazilian Institute of Geography and Statistics website (IBGE 2017, 2018a). In the municipality level regressions, productivity (kg/hectare of planted area) is assigned to its respective harvest year (i.e., no lags or leads). Table 2.1 summarizes the data set, source, and procedures to each variable at municipality-level.

Variable	Min.	Max.	Mean	Std. deviation	Description
Soy productivity (kg/ha/year)	100	4860	2381	654	Data collected from IBGE (2018a), for each Cerrado municipality.
Annual temperature (average in Celsius)	17.65	29	23.85	1.85	Temperature average (Celsius/year) and total precipitation (mm/year) for each polygon of the Cerrado municipalities, considering the harvest period from November to May of the following year. The statistics were processed in GEE, using the original rasters from the Copernicus Climate Change Service (2017) and polygons from IBGE (2010, 2017).
Annual precipitation (total in mm)	393.7	2684.4	1444	275	
Annual irrigated area (hectares)	1.12	65930	1666	4667	Data by municipality, available from the National Water Agency (ANA & Embrapa, 2019), from 1985 to 2017.

Table 2.1: Data summary for variables of interest in the Cerrado municipalities, from 1980 to 2018.

The data for the extent of the Cerrado biome were obtained from the IBGE website (IBGE 2010), and the Matopiba boundaries from the Embrapa website (Embrapa/GITE. 2014d), both in a vector GIS format (.shapefile). These polygons were intersected with the Brazilian municipalities' shapefile (IBGE 2017) to determine the area of analysis in GEE and ArcGIS. In the Cerrado, the polygons of analysis are composed of 1,388 municipalities, of which 322 (23%) are in Matopiba. The period considered is from 1980 to 2018, resulting in a total of 54,171 observations for the Cerrado, and 12,558 (23%) for the Matopiba subregion. The lack of data for some years and particularly for some municipalities early in the time series, forced those observations to be dropped from the analysis (see the final *n* in the results). Therefore, dataset is an unbalanced panel.

Farmer's survey

A questionnaire was administered to 90 farmers throughout 2017, and the data collected covered a period from 2009 to 2016. I adopted a randomly stratified sampling strategy according to (i) the size of the farms, in the Rural Environmental Register (CAR in Portuguese acronym), a georeferenced digital registry of all private properties in Brazil that is available for download (MMA, n.d.); (ii) farms of different sizes in the four states of MATOPIBA – Maranhão, Tocantins, Piauí and Bahia; (iii) classes of edaphoclimatic conditions (i.e., precipitation and temperature). Figure 2.1 illustrates the stratified random sample distribution (n=90). The 90 farms had an average of 7,383 hectares, with a total of 657,078 hectares, the planted area ranged from 80 to 31,000 hectares, and soy productivity from 1.2 to 4.2 ton/ha. Budget constraints prevented me from obtaining a larger sample size. The research focused on the relationship between crop production and weather fluctuations and did not include the influence of agricultural markets on farmers' decisions because the latter affect all farmers similarly and therefore do not provide heterogeneity required for statistical analyses. The previous semi-structured questionnaire had five types of broad questions (see appendix for more information):

- Background information, such as location (latitude and longitude coordinates), size of farm and agricultural area, date of initial production and purchase of the area.
- Agricultural practices such as the use of irrigation, integrated system such as crop-pasture (for minimum tillage purpose in most of the cases), period of planting.
- Production (in total kg), area planted (hectares), and crops planted.
- Costs of production, including labor (BRL per working hour and number of employees) and machineries (BRL/hectare and working hours per hectare annually).
- Revenues (BRL/ha) and source of any credit to intensify or expand agricultural production.
- Perception about weather extreme events, changes in temperature and precipitation, and mitigation strategies, if any.

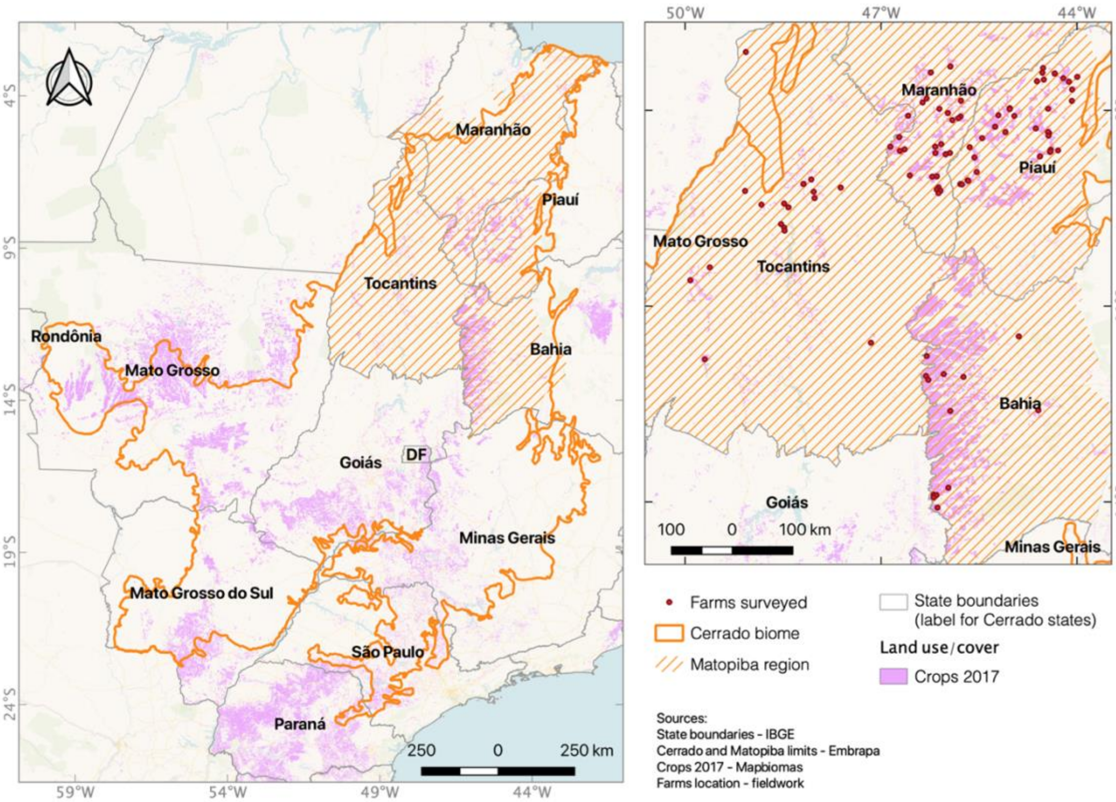

Figure 2.1: Map of the study area and analysis (in three scales: Cerrado, Matopiba, and farms, created by the author).

Table 2.2 summarizes the main variables collected for the farm-level panel regression. Other variables include the agricultural practices reported by farmers. In my sample, 55% of producers use double cropping (i.e., two harvest within a year, usually soy and corn), 40% need to adjust the harvest calendar due to changes in precipitation pattern and dry season, and 35% implement crop-pasture integration as a strategy for minimum tillage. Also, 91% of the farmers uses GMOs for soy crops, 87% pay for technical assistance (i.e., agronomic consultancy), 84% have credit loans (40% of these loans with traders), and the farm is the main income for 85% of them. The public technical support is available mainly for smallholders or experimental areas of Embrapa, therefore, soybean farms and large-scale agriculture rarely have access to this type of assistance despite research on seeds and soil management having great use in these areas.

Variable	Min.	Max.	Mean	Std. deviation	Description
Soy productivity (kg/ha/year)	1200	4200	3003	735.6	Data collected from the fieldwork
Temperature (average in Celsius)	22.47	28.99	26.74	1.17	Temperature average (Celsius/year) and total precipitation (mm/year) for each farm polygon, considering the harvest period from November to May of the following year. For the farm polygon, I considered CAR entry (MMA, n.d.). The statistics were processed in the GEE, using the original rasters from the Copernicus Climate Change Service (2017).
Precipitation (total in mm)	607	2364	1262	335.3	

Table 2.2: Data summary for variables of interest in the farms surveyed, from 2009 to 2016.

Statistical analysis

I estimated the long-term effect of temperature (°C) and precipitation (mm) on soybean productivity (kg/ha) using panel data regression at municipal level within the Cerrado biome, from 1980 to 2018. Using a multi-scalar dataset, I also compared the variables and results with farm-level regressions in the subset region of Matopiba (2009-2016). As the climatic effect is non-linear and spatially heterogeneous, I used different regression model specifications that consider variations across time and between space (municipalities or farms). For instance, my fixed effect model estimated the marginal effect of each variable across time and removed potential biases of omitted time invariant variables (e.g., soil quality). Meanwhile, the Random Effect model observed the variation between individuals and allowed my assessment of spatial time-invariant heterogeneity for municipalities. I implemented and compared three estimators: a pooled OLS, fixed effect (FE), a random effect (RE).

I followed the literature in adding quadratic terms for temperature and precipitation (Burke et al 2015, Lobell et al 2011, Schlenker & Roberts 2009), in order to allow for non-linear effects between temperature and precipitation with yield. For instance, Burke et al (2015) and Schlenker & Roberts (2009) found that soybean and other crops worldwide are hampered by extreme conditions of heat and precipitation; usually the threshold for annual average temperature that hinders the productivity of those crops is between 20 and 30 degrees Celsius. The quadratic coefficients allow for the estimation of turning points when temperature and precipitation begin to negatively affect yields. Also, in all models I considered the coefficients of log-level model to estimate the percentage changes in productivity for each unit variation in the regressors. The log-level model coefficients can be interpreted as a percentage change in Y when the X regressor increases by one. Moreover, some variables (e.g., irrigated area) are not available for the entire period analyzed, so by removing the NAs I created an unbalanced panel analysis.

To avoid spurious correlation, I detrended yield and isolated the linear growth trend caused by technology and differences in the land management. If ignored, the trend aspect exaggerates the explanatory power of regressors and lead to erroneous conclusions, because the tendency (positive or negative) of values over time is not entirely caused by the independent variable. Following Wooldridge (2013), I applied two methods to remove the trend effect; first I used the residuals of yield regressed on t as an independent variable to the fixed effect model, while for the random effect model the year was added as a regressor of state-specific trend.

See below the regression model for the municipality-level, from 1980 to 2018.

$$log\left(y_{i,t}\right) = \alpha + c_i + \beta_1 T_{i,t} + \beta_2 T_{i,t}^2 + \gamma_1 P_{i,t} + \gamma_2 P_{i,t}^2 + \delta I_{i,t} + e_{i,t}$$

Where:

y = soy productivity in each municipality i in year *t*.

α = the intercept.

c_i = the municipality fixed effect.

T = annual average temperature (Celsius).

P = annual total precipitation (millimeters).

I = irrigated area (hectares).

β_1 , γ_1 , δ are the respective coefficients.

T^2 and P^2 are the quadratic terms for T and P.

β_2 , γ_2 are the respective coefficients of the quadratic terms.

e = error term.

The farm-level data was not detrended for two reasons: (i) the analysis was short-term (2009-2016), so I assumed that there were no major technological improvements during that time; and (ii) with data at the farm level, I controlled for agricultural practices reported by farmers.

See below the regression model for the farm-level, from 2009 to 2016.

$$log\left(y_{i,t}\right) = \alpha + c_i + \beta_1 T_{i,t} + \beta_2 T_{i,t}^2 + \gamma_1 P_{i,t} + \gamma_2 P_{i,t}^2 + \delta m_{i,t} + e_{i,t}$$

Where:

y = the productivity (kg/ha) to each farm i in period t.

α = the intercept.

c_i = the farm fixed effect.

T = annual average temperature (Celsius).

P = annual total precipitation (millimeters).

β_1 , γ_1 , δ are the respective coefficients.

T^2 and P^2 are the quadratic terms for T and P.

β_2 , γ_2 are the respective coefficients of the quadratic terms.

δ = a vector of coefficients related to the matrix m of dummy variables for agricultural practices (i.e., irrigation, crop-pasture integration, second harvest, calendar adjustments).

e the error term.

As a complementary analysis to the longitudinal data, I evaluated the use efficiency of inputs (capital, labor, land) on the production of the farms. For this, I used a classic production function (Cobb-Douglas), in the cross-section data for the 2016, according to the procedures of Arima (1998). The reason why I used cross-section for 2016 is the availability of production costs reported by farmers only for that year. The production function represented by the Cobb-Douglas model assumes that the quantity produced (Y) depends on the quantity of inputs (i.e., capital, labor, land). The Cobb-Douglas function is widely used in economics because of its simplicity and ease of estimation. In addition, the sum of the estimated parameters (See below in the equation: alpha, beta, delta) indicates returns to scale. If the sum is equal to one, farms exhibit constant returns to scale; if greater than one, increasing returns, and if smaller than one, decreasing returns to scale. My modeling analysis also estimated the efficiency of agricultural practices. The coefficients of this production function estimate the percentage of change in total production for each unit of variation in capital and labor costs.

First, I considered the total production and inputs per farm. I ran this model with and without dummy variables for agricultural practices. See below the Cobb-Douglas conceptual model.

$$\mathrm{Y}_i = a\mathrm{K}_i^{\alpha}\mathrm{L}_i^{\beta}\mathrm{A}^{\delta}e^{\theta\mathrm{D}}e^{\mu_i}$$

Where:

Y = the yield to each farm i, in tons.

a = the intercept.

K = the annual cost of renting machinery, as proxy of capital (BRL currency).

L = the annual cost of labor (BRL currency).

α and β are the partial elasticity for a given input.

A = the crop area, in hectares.

δ = the coefficient for the crop area.

e = the natural number.

D = the dummy variable for a given agricultural practice.

θ = the coefficient for the effect of a given agricultural practice.

μ = the error.

i = the farm's index, 1 to 90.

Second, I calculated the demand for inputs according to the agricultural practice, derived from the previous production cost function. Particularly four variations in demand for input as dependent variables: (i) capital by planted area (K/A), (ii) labor by planted area (L/A), (iii) planted area per ton of soy (A/Y), and (iv) capital by labor (K/L). The purpose was to estimate whether agricultural practices impose different demands on farms. For example, see below the model that examines capital intensity per unit of area.

$$log\ (\mathrm{K}_i/\mathrm{A}_i) = \alpha \mathrm{D}_\mathrm{i} + \beta \mathrm{D}_{credit_i} + \mu_i$$

Where:

K = the annual cost of renting machinery, as proxy of capital (BRL currency).

A = the crop area, in hectares.

α = a vector of coefficients related to the vector D of dummy variables for agricultural practices (i.e., crop-pasture integration, second harvest, calendar adjustments, agricultural credit), considering 1 if the farm uses such agricultural practice and 0 if not. I included a dummy variable for credit due to its relevance to enable technology implementation.

β = the coefficient of the dummy variable D_{credit} for public credit loans.

μ = the error term.

i = the farm's index, 1 to 90.

Due to caveats common to statistical models, I combined the modeling results with the farmers' perspective on the causes and consequences of productivity loss. Moreover, the panel model assumes stationary data, and the results cannot predict the impact of political and economic changes. The production function, on the other hand, does not capture some adaptation strategies (e.g., land abandonment) and the variance of fertility (soil type, fertilizer rotations), soil degradation or conservation. Therefore, I contextualized and validated the results with qualitative questions, describing farmer's adaptation strategies and socioeconomic consequences of extreme weather events in Matopiba. Thus, I discussed the (mis)matching of the results with the farmer's perspective. As suggested by the literature (Vayda, 1983), this approach allows for the progressive contextualization of the results and the historical processes.

RESULTS

Productivity and temperature/precipitation variability

Temperature (T) has an increasing trend in the Cerrado municipalities (Figure 2.2), approximately 1°C higher compared to the beginning of the time series. Also, average precipitation (P) has a slightly decreasing trend, for the 1980-2018 period. However, these overall trends are not uniform across all the regions. For example, in the Matopiba region the average temperature is 5°C higher for all the 1980-2018 period (Figure 2.2, A and B), indicating a stronger warming variability. Moreover, during droughts, the impact on productivity is uneven and varies according to the farmer's property size, natural conditions (e.g., soil), and response in terms of agricultural practices adopted, as illustrated by the bimodal distribution shape in Figure 2.3. Yet, in normal years the distribution of temperature and productivity is similar between Matopiba municipalities and the surveyed farms (Figures 2 and 3), implying some mesoscale patterns.

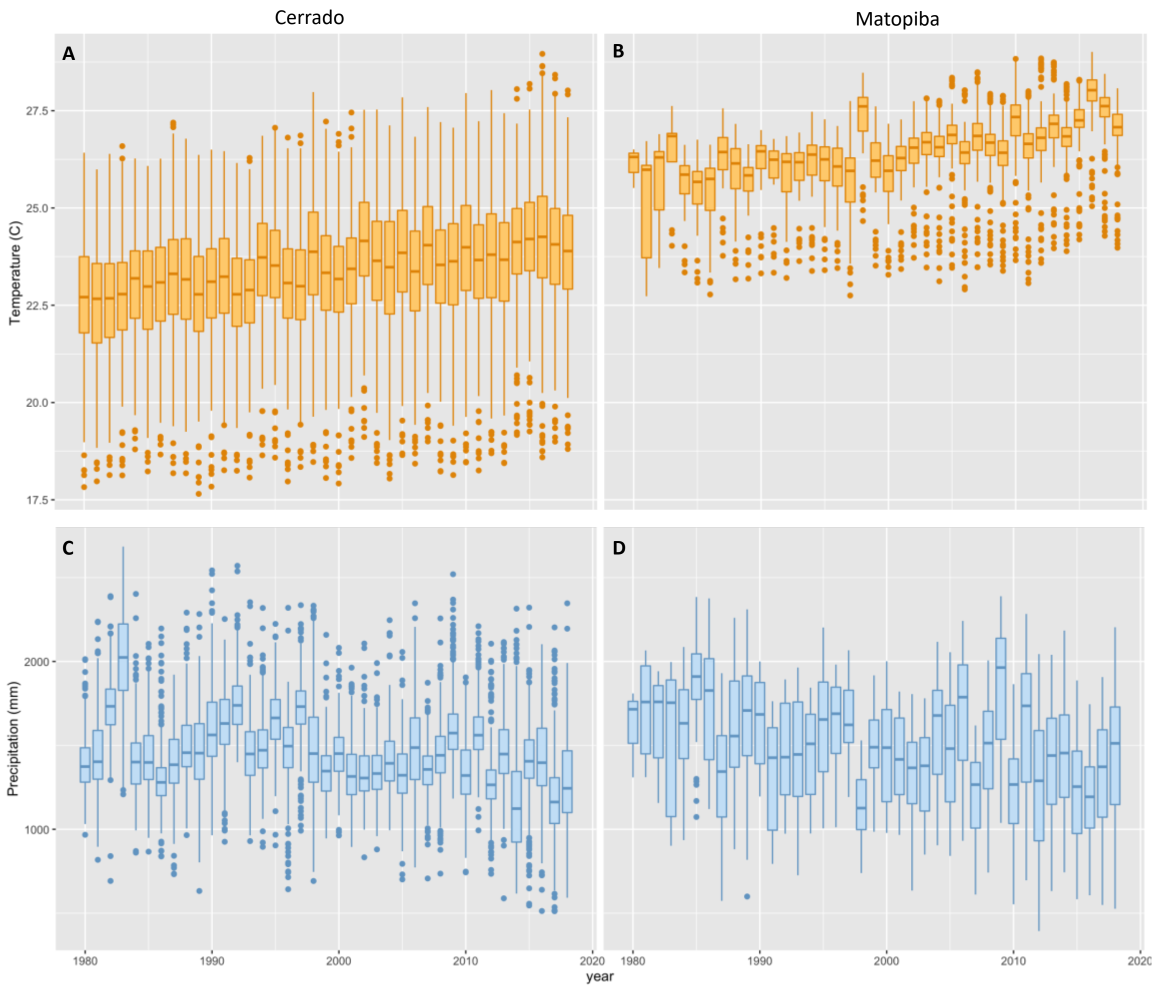

Figure 2.2: Boxplot of the average annual temperature and total precipitation in the polygons of the Cerrado and Matopiba municipalities, from 1980 to 2018. Source: Elaborated by authors with ERA5 Copernicus data.

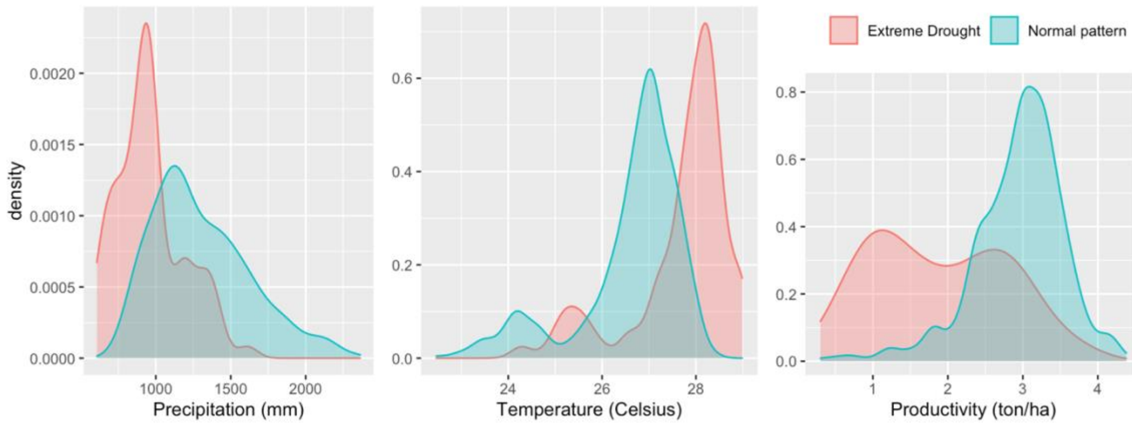

Figure 2.3: Climate variables density distribution to interviewed farmer's in Matopiba (2009-2016). For extreme drought I considered the 2015/2016 harvest calendar. Source: Elaborated by authors with fieldwork data (productivity), and ERA5 Copernicus (precipitation and temperature).

The municipality level regressions indicate that higher temperatures are associated with lower productivities (Tables 2.3 and 2.4). The negative effect of higher temperatures was significant in all models, for all scales of analysis. Rainfall on the other hand has a positive yet small effect on productivity. These results are valid for all models, except for the FE with squared terms (model 1.4), where both the level and quadratic terms were highly significant. All FE models with quadratic terms suggest a non-linear relationship between temperature and productivity for any scale of analysis (Cerrado, Matopiba, or farm level) (Tables 2.3, 2.4 and 2.5). Precipitation had the same non-linear relation, except for the Matopiba (Table 2.3, model 2.4). Based on the model 1.4 (Table 2.3), I estimated that an average annual temperature above ~27°C are harmful to soybean yields. This estimated temperature threshold for soybean is consistent with the literature (Schlenker & Roberts, 2009; Burke et al, 2015) and indicates that future unsuitable areas for agriculture will be in the northern portion of the Cerrado according to future climate projection. Similarly, the risk of crop failure may increase in most of the biome due to the expected temperature increases (see Figure 3.3, in Chapter 3).

In terms of partial effects, a 1°C increase in temperature reduces productivity by 1.5 to 5.5% in the Cerrado municipalities (Table 2.3). Meanwhile, a 10 mm increase in rainfall is associated with a 0.01% to 0.14% increase in yield in the Cerrado (Table 2.3). The partial effect was calculated only in the models without quadratic terms (Table 2.3). In general, the FE is the preferred estimator to partial effects because the municipality heterogeneity (or unobserved time-constant characteristics c_i) is removed in the estimation procedure (i.e., within transformation). Hence, FE results in consistent estimators, even if the error term is correlated with these unobserved characteristics. This means that I am more confident in models 1.2 and 1.3 to estimate the effect on productivity to the Cerrado. Both FE and RE models rely on the so-called strict exogeneity assumption. For instance, it assumes that future explanatory variables values do not react to current changes or shocks to unobserved effects. RE models need an additional assumption, that the municipality level fixed effect is also uncorrelated with unobserved factors. Although RE models need strong assumptions to be consistent, they can be nonetheless informative and may add robustness to the analyses. RE model 1.6 (Table 2.3) is my preferred specification to interpret the overall context of soy yield in the Cerrado. Subsequently, irrigation in combination with other technologies (represented by the state-specific variable) are the main factors for higher yields, each 10mm of precipitation has a positive effect of 5-12% on yield, and higher temperatures have a negative effect; these results are consistent with the FE models.

For the Matopiba subset, the FE model presents a lower partial effect of temperature and a significant effect of precipitation on yield (Table 2.4, models 2.2, 2.3 and 2.4). The negative effect of precipitation on yields at municipal level of Matopiba is unexpected, although the magnitude of the coefficient represents an insignificant effect (0.5% reduction in productivity for every 100 mm). The underreporting of irrigated area and information gaps in the time series may also explain the unexpected effect of precipitation. Again, my preferred specification is the RE model (Table 2.4, model 2.5) due to its overall consistency with the other results. According to the model 2.5, the productivity in the Matopiba is more sensitive to higher temperatures; a 1°C increase in temperature reduces productivity by 7.7%. Moreover, 10mm of precipitation are correlated with 17% higher productivity. The higher sensitivity of Matopiba is expected due to the uneven spatial pattern of the temperature trend in the territory, as depicted in Figure 2.4. In the eastern part of the Cerrado (including Matopiba), the temperature increased by more than one standard deviation for the entire period of 1980-2018. Continued increase in temperature above the standard deviation (Figure 2.4.A) is a bad omen for farmers in the region and might indicate an uncertain future due to the relationship between temperature and yields. Figure 2.4.B indicates that most of the productivity loss during 2015 occurred in the municipalities within the Matopiba.

The regressions for the interviewed farms follow the same patterns observed at the municipality level. For example, the non-linearity of precipitation was significant (model 3.5) and the negative effect of the temperature increases was observed in all models (Table 2.5). Also, agricultural practices did not change the negative relationship between increased temperatures and productivity, but these new variables attenuate the effect of precipitation in the FE and OLS models (Table 2.5). In all models, the practice of double cropping (second harvest in the same year) was the only significant one for increasing productivity. However, at the farm level, I must interpret the RE and FE with caution because the addition of agricultural practices in response to unobserved shocks is more likely and this would violate the strict exogeneity assumption (such variables are probably correlated with the error term). Nonetheless, the FE controlled by agricultural practices is my preferred estimator (model 3.4). Additionally, the R^2 in tables 2.3 to 2.5 indicates that as I downscale the analysis and the heterogeneity decreases, the fixed effect models explain more of the variation in yield. Interestingly, the estimated magnitude of the FE model et the farm-level (Table 2.5) reflects the impact of the 2015/2016 drought in the municipalities of Matopiba: each 1˚C increase in temperature is associated with a ~34% reduction in productivity.

	Cerrado, 1980-2018 (n = 1088, T = 1-39, N = 23350)					
Model	(1.1) OLS	(1.2) FE	(1.3) FE	(1.4) FE	(1.5) RE	(1.6) RE
a (intercept)	3.39E-02				7.60E+00***	7.37E+00***
Temperature (C)	-2.12E-03**	-4.28E-02***	-5.47E-02***	3.01E-01***	-1.81E-02***	-1.48E-02***
Temperature (C) sq.				-7.49E-03***		
Precipitation (mm)	1.15E-05*	-2.94E-05	-1.72E-05	1.39E-04**	4.78E-05***	1.17E-04***
Precipitation (mm) sq.				-5.63E-08***		
State-specific trend (year)				2.06E-02***	2.02E-02***	4.42E-06***
Irrigation (ha)			1.93E-06			1.13E-01***
R^2	0.001	0.007	0.012	0.45	0.90	0.87
Detrended variables	Yes (detrended-level)			No		
*p-value: . <0.1, *<0.05, **<0.01, ***0*						

Table 2.3: Panel model results to Cerrado municipalities from 1980 to 2018.

	Matopiba, 1980-2018 (n = 208, T = 1-39, N = 3000)					
Model	(2.1) OLS	(2.2) FE	(2.3) FE	(2.4) FE	(2.5) RE	(2.6) RE
a (intercept)	7.62E-01***				8.76E+00***	7.60E+00***
Temperature (C)	-3.24E-02***	-1.70E-01**	-2.35E-01***	1.37E+00***	-7.74E-02***	-0.0146
Temperature (C) sq.				-3.10E-02***		
Precipitation (mm)	6.95E-05***	-9.71E-05***	-5.44E-04**	0.000159	1.66E-04***	-1.24E-04 .
Precipitation (mm) sq.				-9.59E-08*		
State-specific trend (year)				3.52E-02***	2.92E-02***	1.31E-01***
Irrigation (ha)			2.20E-06			-0.00000149
R^2	0.024	0.075	0.083	0.43	0.882	0.417
Detrended variables	Yes (detrended-level)			No		
*p-value: . <0.1, *<0.05, **<0.01, ***0*						

Table 2.4: Panel model results to Matopiba municipalities from 1980 to 2018.

	Farms, 2009-2016 (n = 73, T = 8, N = 584)						
Model	(3.1) OLS	(3.2) OLS	(3.3) FE	(3.4) FE	(3.5) FE	(3.6) RE	(3.7) RE
a (intercept)	5.80E+00***	5.76E+00***				7.26E+00***	7.25E+00***
Temperature (C)	-9.45E-02***	-9.31E-02***	-3.04E-01***	-3.47E-01***	2.59E+00***	-1.45E-01***	-1.46E-01***
Temperature (C) sq.					-5.35E-02***		
Precipitation (mm)	4.16E-04***	3.74E-04***	9.41E-05 .	1.69E-04**	1.29E-03***	3.31E-04***	3.08E-04***
Precipitation (mm) sq.					-4.40E-07***		
Irrigation		8.42E-02		-2.18E-02			1.32E-01
Crop-pasture integration		-1.05E-02		4.67E-03			-6.00E-03
Second harvest		8.91E-02**		2.83E-02***			9.33E-02*
Calendar adjustments		1.89E-03		8.41E-03			1.92E-02
R^2	0.24	0.26	0.29	0.32	0.37	0.23	0.24
*p-value: . <0.1, *<0.05, **<0.01, ***0* *Dummy variables were multiplied by year to be used in FE (i.e., irrigation, crop-pasture, second harvest, calendar adjust)*							

Table 2.5: Panel model results to Matopiba farms from 2009 to 2016.

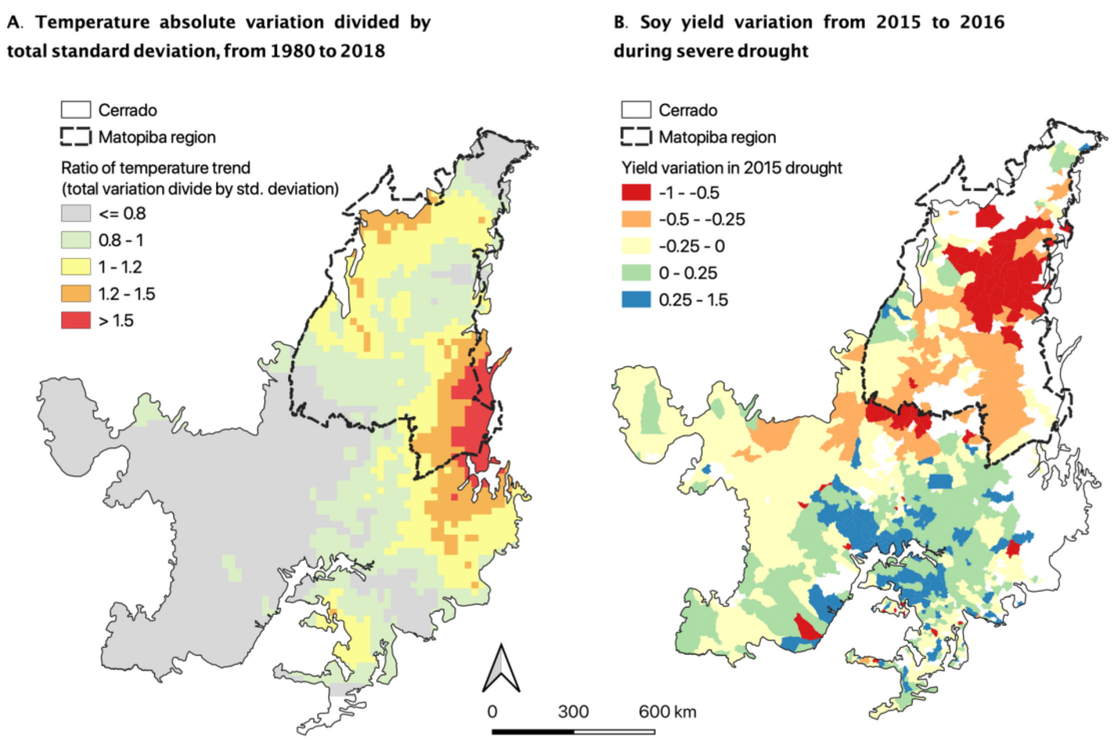

Figure 2.4: Trend temperature increase divided by the standard deviation from 1980–2018 (A); and soy productivity loss/gain from 2015 to 2016 to the Cerrado municipalities during a severe drought (B). Source: Elaborated by the authors with data from IBGE (2018a), Copernicus Climate Change Service (2017).

Production function

Despite the negative effects of higher temperatures on crop yields, farmers observe essentially the gains in scale of production and short-term fluctuations in the weather. For most respondents, the variations in temperature and rainfall are cyclical and the expected productivity is often believed to be result of modern inputs and good agricultural practices (details of farmers' perceptions in the next section). Thus, I examined this productivity hypothesis in a formal economic function and evaluated the efficiency of agricultural practices and the effect of economies of scale. Not surprisingly, according to the production function, the planted area and machinery expenses (BRL/year according to hours required) were the main factors that explain production levels during the analyzed period of 2009-2016 (Table 2.6, model 4.1 and 4.2). The importance of machinery validates the importance of credit policies to farm expansion in the Cerrado, even though its effect varies according to the inclusion of other factors. Moreover, the practice of double cropping was the only significant variable that explained higher crop production in combination with other factors of production (model 4.2). The sum of the coefficients was 1.04 (model 4.1) and 1.2 (model 4.2), indicating constant returns to scale. Also, testing for joint hypothesis, the results indicate that I cannot reject the null hypothesis of constant returns (*p-value* = 0.14).

The models 4.3 to 4.6 (Table 2.6) assess the demand for inputs according to the area and access to public credit. The results indicate that farms with second harvest and crop-pasture integration demand less capital per area (model 4.3, at the confidence level of 0.05). The practice of the second harvest also decreases the demand for area (model 4.5) and the capital-labor ratio (model 4.6), at the confidence level of 0.10. The crop-pasture integration increases the demand of labor per planted area (model 4.4) and capital (model 4.6). Access to public credit was not significant in my analysis, probably because most farmers are funded by soy traders (e.g., Cargill, Amaggi, Bunge). A common practice in the region is to finance inputs in advance by committing future production sales to traders. The models that estimate the demand for inputs have a low explanatory power ($R^2 \leq 0.2$), partly because I did not include variables related to the individual characteristics and other financial incentives (e.g., tax, access to other sources of funding).

Although the production function captures the relevance of economic inputs, it does not indicate the socioeconomic impact of droughts and weather extreme events. The attention to short-term economic gains and weather fluctuations explains the farmland expand in such risky region. The next section dives into the farmer's perception on climate variables and implications of weather extreme events.

	Farms, 2009-2016 (n=90)					
	model 4.1	model 4.2	model 4.3	model 4.4	model 4.5	model 4.6
Dependent variable	Ln(Y)	Ln(Y)	Ln(K/A)	Ln(L/A)	Ln(A/Y)	Ln(K/L)
Independent variables						
a (intercept)	0.02	-0.87	5.07 ***	1.61 ***	-1.00 ***	3.46 ***
Labor (BRL total)	0.05 *	0.03 .				
Machinery (BRL total)	0.11	0.28 .				
Crop area (ha)	0.88 ***	0.72 ***				
Double cropping		0.12 *	-0.11 **	0.29	-0.09 .	-0.4 .
Crop-pasture integration (minimum tillage)		0.04	-0.09 *	0.49 *	-0.03	-0.60 *
Crop calendar adjustment		-0.03	-0.01	-0.2	-0.05	0.21
Credit access		0.02	0.04	0.34	0.04	-0.31
R^2	0.97	0.97	0.20	0.10	0.07	0.14
R^2 adjusted	0.97	0.97	0.16	0.06	0.03	0.10
Degree of freedom	80	76	79	79	79	79
Sum of coefficients	1.04	1.20				
*p-value: . <0.1, *<0.05, **<0.01, ***0*						

Table 2.6: Results of the production function for the 90 soybean farms surveyed in Matopiba.

Farmer's perception on climate variables and barriers for production

According to the farmers I interviewed, weather oscillation (meaning temperature and rainfall fluctuations for them) is the main barrier to increasing production (33%)

(Figure 2.5), mainly due to its influence in the droughts. Also, most farmers recognize that temperature is increasing in the region and that droughts are associated with the El Niño frequency. However, they claim that changes in temperature and rainfall pattern are cyclical fluctuations and not a permanent or long-term trend (Figure 2.6). Although the impacts of higher temperatures, most farmers reported that a shorter rainy season is of greater concern for the crops. Only 4% of respondents stated that there was no change in the rainfall pattern and 15% did not perceive changes in temperature. Some interviewees mentioned global warming as a culprit for those changes, but they doubt its anthropogenic origin or that regional vegetation loss is related to synoptic moisture transport and rainfall. Concurrently, 77% of farmers agreed that native vegetation has benefits and they mentioned ecological equilibrium, conservation of natural springs, water resources, and humidity. The main adaptation strategies of these landowners are calendar adjustments to delay or anticipate soy harvest (29%), minimum or no-tillage techniques such as crop-pasture integration (23%), rotation of crops (17%), or switch to different crops and varieties of seeds (6.5%) (Figure 2.7).

Other barriers to increasing productivity include political and economic factors, such as credit access (17%), transportation logistics (15%), technical assistance and labor capacity (both with 9%), shown in Figure 2.5. Most of the properties surveyed were in financial recovery after sequential losses incurred during the drought of 2015/2016. Most farmers depend on annual credit to maintain crops (83% have loans) and the harvest losses reduced their collateral for bank loans. However, according to the interviews, small producers have difficulty accessing credit after extreme weather events due to the lack of guarantees, with loss of production and high cost of recovery. The impacts are uneven to farmers in different conditions. For instance, in drier regions (i.e., Piaui, and Bahia) smallholders planned to abandon farming altogether or shift to different crops after the

2016 drought and related indebtedness, while large producers expressed interest in expanding activities as conditions improved in 2017. The uncertainty and expectations can be summed up in the words of an indebted rural producer:

> The farmer carries the country on its shoulders, but the government does not care because in Brazil agriculture does not break. Whoever breaks is the farmer. If I go bankrupt, another one comes, buys my land and continues to produce, and apparently nothing changes in the country's general production statistics (soybean producer interviewed in Matopiba region, 2017).

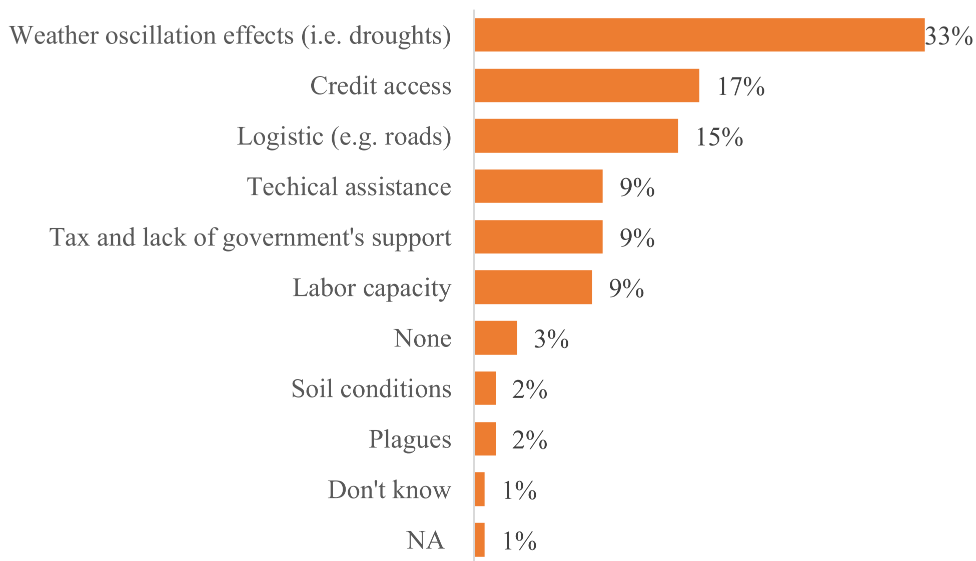

Figure 2.5: Answers to the question “what is the main barrier to increase production?”, in percentage. Source: Fieldwork (n=90, N=127).

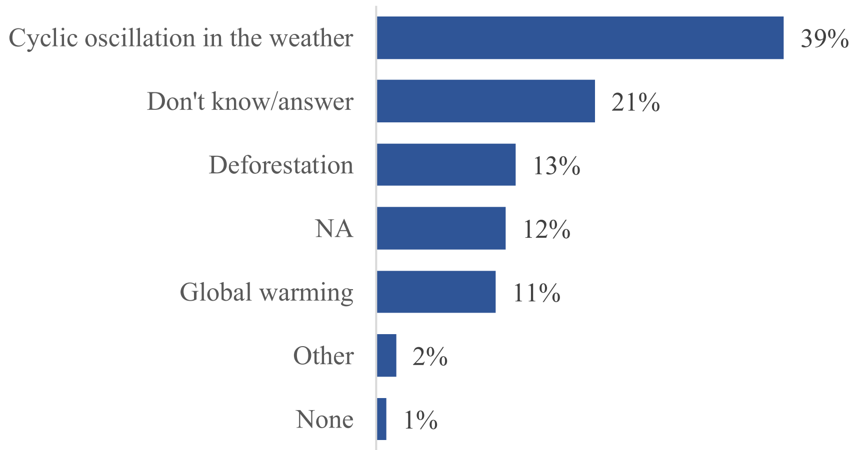

Figure 2.6: Answers to the question “what is the causes of changes in temperature and rainfall patterns?”, in percentage. Source: Fieldwork (n=90, N=105).

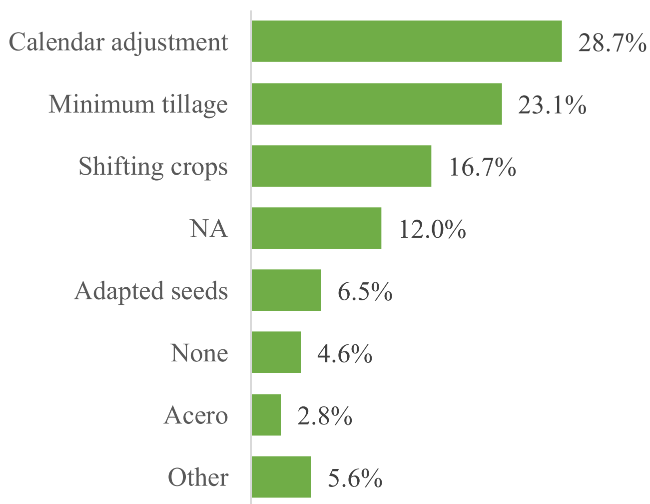

Figure 2.7: Answers to the question “what is your adaptation strategy to changes in temperature and precipitation?”, in percentage. Source: Fieldwork (n=90).

DISCUSSION

The Cerrado is the Brazilian biome with the largest crop production, mainly soybeans for export. In recent decades however, farmlands have expanded over more arid environment without adequate precipitation for rainfed agriculture. Increasing temperatures have consequences for agriculture, such as water deficit (Assad et al 2013, Latrubesse et al., 2019). My study estimated that every ~1°C increase in temperature was associated with a reduction of 4% in soybean yield is expected, using data for the Cerrado region since 1980. During the 2015 drought, productivity was 33% below the average crop productivity in the previous year, with greater intensity in the ecotone between the Cerrado and the semi-arid biome (Matopiba region). Moreover, I estimated that average annual temperatures above ~27°C are harmful for soybean yields. Hence, these results combined with the higher temperature projections indicate the necessity to assess the risks and expectations of gains from agricultural expansion in certain regions vulnerable to rainfall shortage and water availability. To complement the analysis, I identified through interviews the socioeconomic impacts on a sub-regional scale (i.e., Matopiba), which include increased indebtedness and land concentration.

Interestingly, the perception of farmers seems constrained to short-term fluctuations and concentration of operations into larger farms. However, the technologies developed during the Cerrado conquest (e.g., adapted seeds, heavy liming) have limited historical adaptation to extreme heat (Schlenker & Roberts, 2009) and create dependency on capital availability in the form of expensive investments in irrigation. Furthermore, agricultural credit allows the purchase of inputs and technology to adapt to the conditions in the Cerrado, but also induce continuous expansion in areas with little information on future climate risk. (Costa et al., 2020; Richards & Arima, 2018). Unfortunately, I did not assess the role of international markets and future prices on farmer's decision-making process and land change. Evidence so far points to increasing edaphoclimatic restrictions in the semi-arid ecotone, where farmers and local communities seem to be vulnerable to drought shocks (Costa et al., 2020). Also, although short term weather fluctuations and deviations from the normal are expected, a growing number of studies relate those fluctuations as consequences of long-term changes in temperature (Collins et al., 2013; Pires et al., 2016; Anderson et al., 2017).

The trend of increasing temperatures will continue for the next decades (IPCC, 2020), extending the drought periods and affecting the demand for irrigated agriculture in the Cerrado (Latrubesse et al., 2019; Pires et al., 2016). The impact of droughts has increased in recent decades, including wildfires, water deficit, and reduction in crop productivity (Cunha et al., 2019). According to Anderson et al (2017), the weather fluctuations caused by El Niño South Oscillation represents a risk for agriculture and is related to recent crop losses in Brazil. Despite the statistically non-significant effect of central pivots in maintaining long-term yield (tables 2.3 to 2.5), this seems to be the main climatic adaptation in the recent history of Cerrado. From 2000 to 2017, the area irrigated by central pivots in the Cerrado increased from 433,107 to 1,222,409 hectares (ANA & Embrapa, 2019). This combination of rainfall shortage and expansion of irrigated area may affect the practice of double cropping, which is the main significant practice for increasing productivity in my model (Table 2.5). Without proper technical-scientific assessment and land management policies, regions as Matopiba may become the Brazilian version of the United States' Dust Bowl, with prolonged periods of inadequate environmental conditions, inconsistent with initial expectations of financial gain.

Global warming is expected to affect crops productivity across the world, mainly in tropical regions due to water stress, with a potential reduction in food supply and impact on food prices (Burke et al., 2015; Pires et al., 2016; Lobell et al., 2011, Zhao et al., 2017). Therefore, solutions to increase production must tackle climate adaptation/mitigation and food security issues (Vermeulen et al., 2012). The options for mitigation aim to reduce emissions and local impacts on vegetation and keep the ecological functionality of water sources (i.e., rivers, streams). Meanwhile, adaptation strategies may create conflicts with industrial agriculture stakeholders because it typically involves diversification of agricultural activities with reduced use of fertilizers (i.e., nitrogen, phosphorus), such as agroecological practices and crops adapted to a new the climate state, but with lower yields (Vermeulen et al., 2012). The general goal of food supply while reducing risks of crop losses from climate may be beyond the regional scale, as they require deep changes in the food system itself, including consumption choices, international trade, development and transfer of technology, public policies, and capital flow.

My estimates are consistent with the literature, but there is an important caveat about my inability to account for concentration of CO_2 in the atmosphere and its fertilization effects on soybean yields. Some authors claim that the reduction in productivity due to warmer environments can be compensated by the CO_2 fertilization, e.g., Lobell et al (2011) considers a value of ~3%. However, the magnitude of the CO_2 effect is controversial in the literature. For example, Ainsworth et al (2008) and Long et al (2005) claim that laboratory and field studies overestimated the positive effect of CO_2 on the crop yields. Ainsworth et al (2008) argues that CO_2 in the atmosphere can benefit invasive weed species as much as the target crop, affecting productivity and leading to higher production costs. In a methodological note, Schlenker & Roberts (2009) suggested that the effects of CO_2 cannot be accounted for in a regression analysis because it is impossible to separate CO_2 concentration from technological change. However, if the error term of the panel analysis does not covary with the other regressors, these uncertainties do not bias my estimates. My results are still valid in suggesting that the increase in temperature reduces soybeans yields, with a pertinent impact in future scenarios of climate change.

In short, the average increase in temperatures represents uncertainties for long-term financial gains in marginal agricultural expansion areas such as the Matopiba. Hence, private and public actors must better assess the risks of agricultural expansion and take measures to mitigate or adapt land use activities to extreme weather events, particularly higher temperatures and lower precipitation. For example, reduction of land clearing by agribusiness are necessary to avoid compromising the microclimate and the loss of soil due to changes in the water balance (Coe et al., 2011; Silverio et al., 2015; Coe et al., 2017). Moreover, the socioeconomic implications of ENSO events demand better territorial planning of farmland growth and related incentives. For instance, state and federal governments should reevaluate plans that encourage agricultural expansion in climatic risky areas (e.g., PDA for Matopiba), and create mechanisms to strengthen socio-environmental resilience and food security through local supply chains and crop diversification, targeted mostly towards smaller landholders.

Chapter 3: Land change and future climate in Cerrado biome

As global projections of higher temperatures are coming into fruition (IPCC, 2020) and affect crop productivity (see previous chapter), it is important to assess trends in land change for landscape management and to avoid exposing farmers to unnecessary risks. Geospatial technologies and land change modeling have been used to monitor and inform policy making (Lambin et al., 2014; Research Council, 2014; Verburg et al., 2019). For example, Brazilian tropical forests (Amazon and Atlantic Rainforest) have been monitored since the 1980s by PRODES (Monitoring the Brazilian Amazon Forest by Satellite), in order to implement land-policies such as control of wildfires and deforestation (Tasker & Arima, 2016). Moreover, several studies have pointed out the impact of land clearing on water scarcity and other ecosystem services by using spatial explicit models (Allan, 2004; Coe et al., 2011; Latrubesse et al., 2019; Strassburg et al., 2016). However, the impacts of land change in the Cerrado are still poorly studied, despite the accelerated expansion of farmland and its importance for food security (Beuchle et al., 2015; Graesser et al., 2015). For instance, the previous chapter showed that 1°C of temperature increase reduces on average 4% of soy productivity in the Cerrado, but the changes in temperature and farmland expansion are not equally distributed across the biome.

This chapter explores future land change dynamics as they relate to climate projections for temperature and precipitation, up to 2046. First, I built a land change model (LCM) based on Weights of Evidence (WoE) statistical approach, with land cover data from 2001 to 2016. This LCM considers proximate causes (agriculture expansion, distance to roads), underlying causes (GDP, population density, Protected Areas), and environmental endowments (slope and suitability for annual crops). Second, I compared the LCM outputs with the available maps of projected temperature and precipitation

(Brasil, 2020b). In this chapter, my goal is to understand how future climate conditions differ from current climate and what their corresponding impacts on farmland expansion will be. Finally, I briefly discuss the context within which agri-environmental policies are creating push and pull incentives for farmland expansion in the region.

METHODS

Spatial modeling

Based on the land change trends and bioeconomic variables (tables 3.1 and 3.2), I projected the annual land conversion for 2016-2046 period, using Weight of Evidence (WoE) method in the software Dinamica EGO. The lower bound of this period was chosen because it matches the last period (2016) of the datasets that were used in the previous chapter that analyzed the relationship between temperature and productivity. The upper bound limit matches the dataset of projected temperature available until 2046. The model simulates land cover changes with spatial explicit outputs in two major components: (i) the rates of annual agricultural expansion for pasture, cropland, and vegetation regrowth are calculated according to the transition matrix for the baseline period (i.e., 2001 to 2016); (ii) it spatially allocates the amounts of land change by category using the estimates the weights of evidence. The transition matrix and rates of annual agricultural expansion and regrowth are based on the land use/cover map from the Mapbiomas project (Souza et al, 2020). The weights of evidence for spatial allocation considers distance to agricultural areas and other independent variables (distance to roads, Protected Areas, slope, suitability for crops). The following sections detail the model's variables and Figure 3.1 summarizes it.

The WoE is a Bayesian statistical inference method that calculates the influence of spatial variables on land change (Soares-Filho et al., 2004). The WoE breaks continuous variables into binary categories (e.g., distance to roads is converted into a series of buffer distances bins) and calculates probabilities for each bin based on the presence and absence of each land use class with respect to overall extent of the bin. In addition to the landscape simulation, the model project the probability of land change based on historical data. Furthermore, Dinamica EGO also calculates goodness of fitness statistics to validate the models built. This software assumes stationarity, meaning that the underlying processes do not change over time and that the relationship between the variables remains unchanged from the baseline data.

The model considered land use change and related spatial data grouped by subregions with similar socioeconomic context (Figure 3.1, and sections below on subregions and spatial data). Then I calibrated the land change pattern by testing the correlation between the variables and calculating the patch sizes of land change. First, I applied the Cramer's V and Pearson (contingency) tests to assess the correlation between the variables. The low correlation found (<0.4 in all cases) is important to avoid the inclusion of variables that are redundant in explaining land change. Although the modeling considers that a pixel's value tends to be similar to the neighborhood (or autocorrelated), the autocorrelation between independent variables creates two problems: (i) it might violate the statistical assumption that the residuals are independent and uniformly distributed; (ii) and it underestimates the heterogeneity of the land cover, and overestimate patches of the same land cover. Second, for the simulated map to get patterns of land use as close as possible to the observed land cover map, Dinamica EGO has a toolbox that changes the patch size by expanding or contracting land conversion to avoid the so-called salt and pepper pattern, and groups land change into contiguous cells, resulting in landscape and fragmentation patterns that are more realistic. According to the INPE's deforestation data, the average patch size of vegetation loss in the Cerrado is 0.16 km^2 and the standard deviation ~0.90 km^2.

Finally, validation was performed for the 2001-2016 period using a fuzzy similarity approach (Hagen, 2003). Spatial models are assessed in the context of neighborhoods, because even maps without an exact match in the pixel level can show a similar spatial pattern in comparison to the observed land cover. Dinamica EGO validation uses constant decay with multiple windows, or matrices of different sizes to compare neighboring values, by checking the location of the expected pixel category. The similarity index ranges from 0 to 1, with 1 meaning a perfect match between the actual land use map and the projected map. In this study, I compared the minimum values of similarity in the windows of 1x1, 3x3, 5x5, 7x7, 9x9, 11x11, and 13x13.

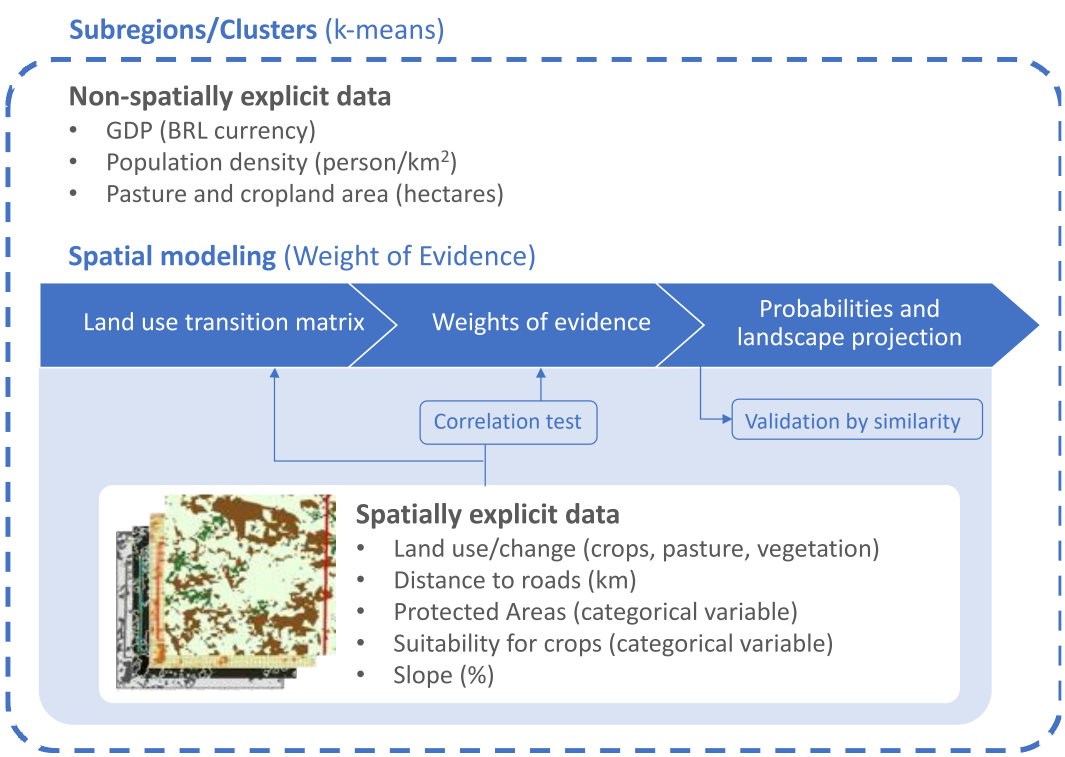

Figure 3.1: Land change modeling framework.

Subregions for land change modeling

The Cerrado biome is spatially heterogeneous due to its extension and varied socioeconomic dynamics, so I divided it into subregions to estimate the effects of different local contexts underlying the causes of land change. Based on empirical observation and literature, I identified the subregions (Figure 3.2):

1. Southeast Cerrado, the older agricultural region mainly occupied by sugarcane activities and pastures, with strong connection to Sao Paulo and the Southeast, the most economically developed region of Brazil.
2. Western Cerrado (i.e., Mato Grosso State), expanding agricultural frontier since 1980, with high clearing rates of native vegetation to pasturelands and increasing cropland over pastures conversion.
3. Matopiba (acronym for the states of Maranhao, Tocantins, Piaui, Bahia), in the north of Cerrado and ecotone with semi-arid region, it is a recent agricultural frontier, with increasing conversion of native vegetation to cropland since 2000s and infrastructure to export commodities through the north of Brazil.
4. The Central region, mostly pastureland, without pronounced agricultural land uses.
5. The fifth region is known as the Brazilian soy belt, in the state of Mato Grosso, due to an increasing soybean area and presence of international traders in the ecotone with the Amazon rainforest.

These regions differ by their occupation processes, edaphic-climatic conditions, population density, urbanization level, GDP composition, and landscape dynamics. I defined the geographical limits of these clusters by applying a k-means analysis with spatial weight of neighborhood to the polygons of the municipalities, in ArcGIS software. The k-means considered the GDP, agricultural land (areas of pasture, crop), population density (person/km^2), as described in Table 3.1. Preliminary clustering analyses indicated seven optimal grouping for the municipalities, however three of them were individual polygons that could be merged in the final subregions for the land modeling. For instance, Brasilia (Brazil's capital) was classified as a unique, probably due its high GDP, but it is located in the Central region. Figure 3.2 shows the final clusters of land change modeling. These subregions are important to better contextualize the results and correlate the risks of future climate change with regional economic characteristics.

	Matopiba	**Soy belt**	**Central area**	**Western**	**Southeast**	**Total for Cerrado**
year 2016						
GDP (BRL currency)	122,399,863	21,264,910	391,751,655	187,815,050	810,490,154	1,533,721,632
Total population	8,510,555	271,934	8,929,537	5,398,667	23,439,741	46,550,434
Population density (person/km^2)	17	5	61	8	91	54
Pasture (ha)	14,080,822	357,324	9,867,015	30,491,629	13,401,512	68,198,302
Cropland (ha)	5,696,811	4,630,154	3,760,074	13,358,148	9,928,908	37,374,095
Native vegetation (ha)	70,198,750	4,069,766	9,909,120	55,717,127	19,847,909	159,742,673
year 2001						
GDP (BRL currency)	16,133,402	1,917,149	56,456,329	23,312,219	171,104,708	268,923,807
Total population	7,080,592	128,355	6,664,906	4,280,237	19,817,473	37,971,563
Population density (person/km^2)	15	2	44	7	75	44
Pasture (ha)	11,755,970	404,599	12,527,722	32,574,281	24,068,868	81,331,440
Cropland (ha)	1,469,094	2,129,127	1,758,879	4,721,833	4,789,848	14,868,781
Native vegetation (ha)	15,340,797	306,894	11,251,002	31,392,753	19,703,744	77,995,189

Table 3.1: Data summary by Cerrado subregion. Source: IBGE (2018b; 2020) and Mapbiomas (Souza et al, 2020).

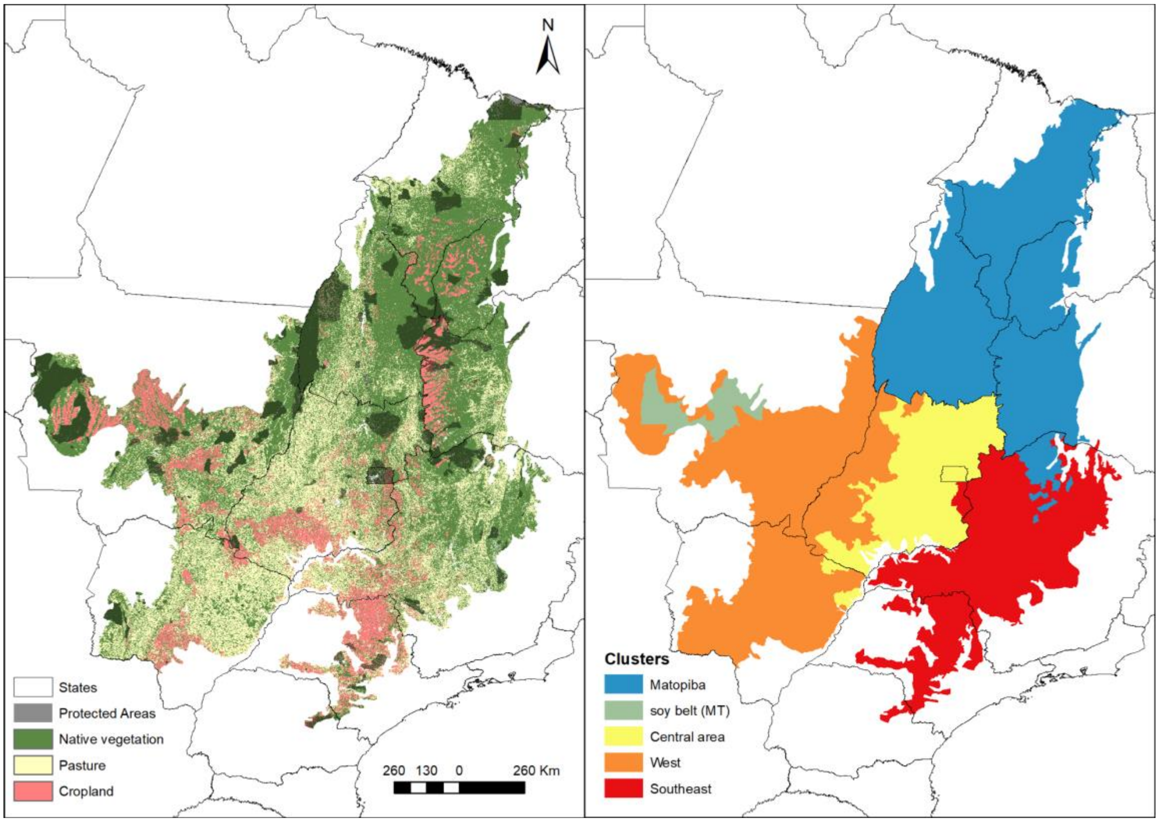

Figure 3.2: Cerrado land use (2016) and subregions for land modeling. Source: Mapbiomas, Brasil (2019), and author's analysis.

Spatial data

The land cover data were obtained from Mapbiomas Project (Souza et al, 2020). This project mapped annual land cover change since 1985 for all Brazilian territory, using Landsat images with 30m of resolution. In order to improve processing in such fine resolution, I reclassified and grouped all different types of land use and cover to five more generic classes: native vegetation, pastureland, cropland, water, other (urban, mangrove, non-observed, other); also, the land change analysis only considered the first three classes. For the "Native Vegetation" class, I grouped the original classes of Native forest and Nonforest vegetation. For the “Pasture” class I grouped the classes Pasture and Agricultural mosaic (most of this latter classification is natural pasture according to the Mapbiomas’ experts I spoke with). The “Crops” class is the same as its homonymous classification from Mapbiomas. Other land uses included Urban areas, Mining, and other non-vegetated land covers. The land change modeling combined the land cover maps with other explanatory variables: distance to roads, Protected Areas, slope, and suitability for annual crops. Table 3.2 summarize the spatial explicit data.

Variable	Description and procedures	Source
Land use/cover	Annual land use/cover, based on Landsat images, 30m resolution	Souza et al (2020)
Roads	Polylines of existing roads in Brazil, clipped to Cerrado and used to calculate a raster of distance to roads	Ministry of Infrastructure (Brasil, 2020a)
Protected Areas	Polygons of Protected Areas, including indigenous land, parks and other set-aside areas for conservation.	Ministry of Environment (Brasil, 2019)
Slope	Estimates of slope in percentage, 30m resolution.	Geological service of Brazil (Brasil, 2010)
Suitability for rainfed crops	Raster with nine categories of suitability for crops, according to soil and climate	GAEZ/FAO

Table 3.2: Spatial data description for land change modeling.

The polygon delineating the boundaries of the Cerrado biome was obtained from the IBGE website, in vector format (.shapefile). This dataset was intersected with the Brazilian municipalities' vector GIS file and other geographic information (i.e., rasters) to determine the area of analysis in the ArcGIS software. There are 1,388 municipalities within the Cerrado. All geographical information were processed in ArcGIS and R software, using the Brazilian Coordinate Reference System SIRGAS 2000 datum. The statistical analysis performed in R software included the tabulation of land chance, prices, and temperature.

Climate scenarios data

Historical and future climatic data were provided by INPE (Brasil, 2020b) and include average annual temperature (Celsius) and total annual precipitation (mm). These were produced from downscaled models from the Coupled Models Intercomparison Project (CMIP) of the World Climate Research Program (WCRP), published in the peer-reviewed literature (Eyring et al., 2019) and in reports of the Intergovernmental Panel on Climate Change (IPCC, 2018). The historical average values cover the period of 1981 to 2010, while the estimates are for 2016-2046, in the lower warming scenario of 1.5 °C (Table 3.3). I chose this specific model simulation because it corresponds to the period analyzed in Chapter 2. This model is more conservative in comparison to the HadGEM3 and MIROC-ES-CHEM models, which assume a 2°C increase in temperature for the same period. In the aforementioned model, the distribution of precipitation does not show major changes in the spatial distribution or in the total annual volume. The trend of the last few decades show that the main change observed in precipitation is in its seasonal intensity (Chapter 2 discuss the effects of precipitation and temperature). On the other hand, the spatial pattern and mean temperature levels are predicted to be much different (Figure 3.3) and are likely to have significant effects on agricultural productivity (results of Chapter 2). Therefore, this chapter focuses the discussion on the relationship between temperature and land change. Figure 3.3 illustrates the mean temperature patterns in the Cerrado.

Model	Timeframe	Variable description
EC-Earth3-HR, GISS-E2-H	Historic, 1981-2010	Average annual temperature (C), 40km resolution
EC-Earth3-HR, GISS-E2-H	Future, 2016-2046	Average annual temperature (C), 40km resolution
EC-Earth3-HR, GISS-E2-H	Historic, 1981-2010	Total annual precipitation (mm), 40km resolution
EC-Earth3-HR, GISS-E2-H	Future, 2016-2046	Total annual precipitation (mm), 40km resolution

Table 3.3: Data description of climatic models. Source: INPE (Brasil, 2020b).

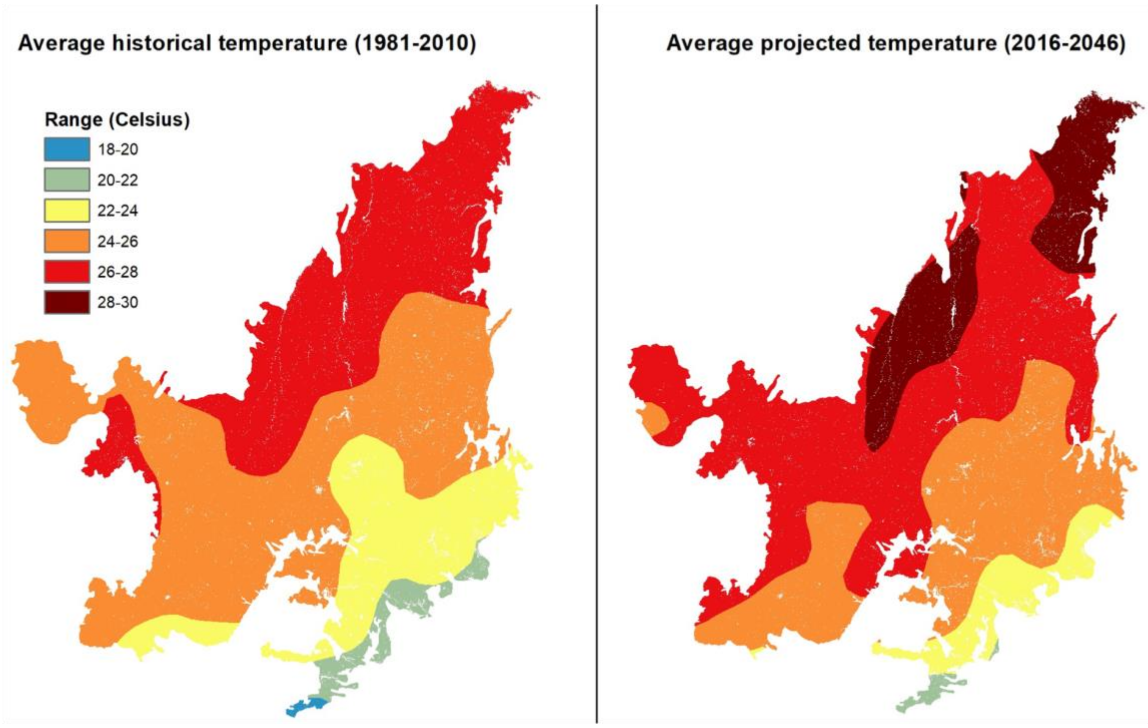

Figure 3.3: Historical and projected temperature in the Cerrado biome. Source: INPE (Brasil, 2020b).

RESULTS

LULC modeling

The area of native vegetation and pasture decreased from 2001 to 2016, while cropland doubled (Table 3.4). However, a net reduction in pastureland was observed because more of it transitioned to croplands than new pastures were formed through land clearing. The transition area matrix (Table 3.4) indicates that 38% of the cropland in 2016 was pasture in 2001 and 13% was converted from native vegetation. Meanwhile, 11% of pasturelands in 2016 were vegetation in 2001 and 1% were cropland. In short, the expansion of cropland over pasture is the largest change between land uses although land clearing still occurs mainly for pasture.

The transition probabilities matrix (Table 3.5) obtained in Dinamica EGO indicates the probability of annual land change, for the observed period of 2001-2016. Pasture to crops is the main land change in the soy belt. For all subregions, the main trend is vegetation regrowth in pastureland and land clearing for pasture. The results of regrowth are consistent with the increasing land abandonment/regrowth (Silva Junior et al., 2020), and investments in agricultural commodities explain the soy expansion in the Cerrado (Fairbairn, 2020). The probability of land change for 2046 indicates that cropland expansion will be concentrated in the north (i.e., Matopiba region), while regrowth and crop over pasture conversion might occurs in the south (Figure 3.4). Pastureland expansion is scattered across the biome. The expansion of crops over pasturelands in the Southeast region is likely due to the much higher profitability of crops and the proximity to the many ports and processing facilities located in the states of São Paulo and Minas Gerais. In total, the model estimated 234,157 km^2 of vegetation loss, for the period of 2016-2050.

The model's WoE indicates that Protected Areas (PAs) have a strong negative weight for the occurrence of land clearing and increases the probability of regrowth inside its areas. Nevertheless, PAs of sustainable use do not halt land clearing, similar to the results of previous studies (Françoso et al., 2015). It is not surprising that PAs are effective on conservation (Monteiro et al, 2020), but the Cerrado does not have many undesignated public areas ("terras devolutas" in Portuguese) available for the creation of new PAs. In a total of 1.03 million km^2 of remaining native vegetation, 490 thousand km^2 are in private protected areas (e.g., set-aside areas protected by law inside rural properties), and only ~23 thousand km^2 has no destination[1]. Although private protected areas cannot be compared or be substitutes of public PAs, those fragments of vegetation can be relevant to the landscape

[1] Estimates based on the rural environmental register of private areas (MMA, *n.d.)*, vegetation of Mapbiomas (Souza et al., 2020), and PAs of the Ministry of the Environment (Brasil, 2019*)*.

connectivity and may complement public PAs. Hence, private protected areas may have greater relevance in the conservation of ecosystem services.

The effect of PAs on reducing the risk of vegetation loss is expected, so I highlight three other comparative aspects with previous studies, such as spatial pattern and competitive land uses. First, the land change rates projected in my model are close to other studies for the Cerrado, for example, Monteiro et al (2020) estimated 302 thousand km^2 of new agricultural areas for the period between 2012 and 2050, while Strassburg et al (2017) projects ~202 thousand km^2 in a business-as-usual scenario for the period of 2012-2050. Furthermore, Ferreira et al (2013) and Lima et al (2018) found the same critical regions at risk of vegetation loss, in the north (Matopiba) and western (Mato Grosso) parts of the Cerrado. Second, my approach considered competitive land uses, between pasture and crops, and regrowth. Strassburg et al (2017) deals with regrowth/restoration as a possible scenario based on public incentives, while I have captured this effect as a trend in recent years. Furthermore, by considering the expansion of pasturelands concurrent with the croplands, I found a lower concentration of land change risk in Matopiba compared to other modeling studies mentioned above, partly due to a greater dispersion of pastures throughout the biome. Ultimately, my model does not address the underlying causes of agricultural expansion, such as global supply chains and the effect of public policies. In the literature, commodity exports and political stability are relevant factors for the advance of land clearing in tropical areas (Barbier & Burgess, 2001), and affect land change of other biomes in South America, such as the Chaco (Gasparri & Grau, 2009; Graesser et al, 2015).

In the validation performed for the 2001-2016 period, my model predicts 807 thousand km^2 of agricultural area (crops and pasture) against the observed 833 thousand km^2. The minimum fuzzy similarity index for 3x3 windows upwards, the case of pixel-by-pixel comparison, ranges from 0.5 to 0.86 and are a function of both the goodness of fit of the model and window test (Figure 3.6). The lowest value of 0.5 used a small window of 3x3 and was found in the soy belt region (state of Mato Grosso). The best match was in Central are of the Cerrado using a window size of 13 pixels. The land change projection is conservative in comparison to the current land cover (Figure 3.5), but this reflects the decreasing rate of vegetation loss in the period before the recent uptick in land clearing (Brasil, 2020b). Also, I ran the land change model in three regional subsets for comparison – without subregion, at municipality level, and using clusters as subregion. In all cases the similarity between the 2016 land cover and the simulated maps is better in clusters' weights of evidence (see the Appendix for the results without subregions and at municipal-level). This comparison of similarities validates my assumption that regional clusters are the ideal scale of analysis for this application because they better capture the regional specificities of land change.

		2016			**Total in 2001**
		Native vegetation	Pasture	Cropland	
2001	Native vegetation	893,039.38	84,193.27	30,634.73	**1,007,867.37**
	Pasture	24,155.22	689,192.30	86,388.01	**799,735.53**
	Cropland	485.24	6,107.35	110,819.20	**117,411.79**
	Total in 2016	**917,679.84**	**779,492.92**	**227,841.94**	

Table 3.4: Land cover transition area matrix (km^2) from 2001 to 2016, in Cerrado. Source: Elaborated with data from Souza et al (2020).

From	**To**	**Matopiba**	**Soy belt**	**Central area**	**West**	**Southeast**
Native vegetation	Pasture	0.0092	0.0068	0.0295	0.0198	0.0229
	Crops	0.0037	0.0110	0.0022	0.0026	0.0033
Pasture	Nat. Veg.	0.0386	0.0286	0.0261	0.0224	0.0315
	Crops	0.0024	0.0618	0.0129	0.0081	0.0172
Crops	Nat. Veg.	0.0063	0.0042	0.0068	0.0059	0.0089
	Pasture	0.0029	0.0031	0.0084	0.0066	0.0076

Table 3.5: Results of annual transition probabilities matrix by land cover and subregion. Source: Author's analysis in Dinamica EGO.

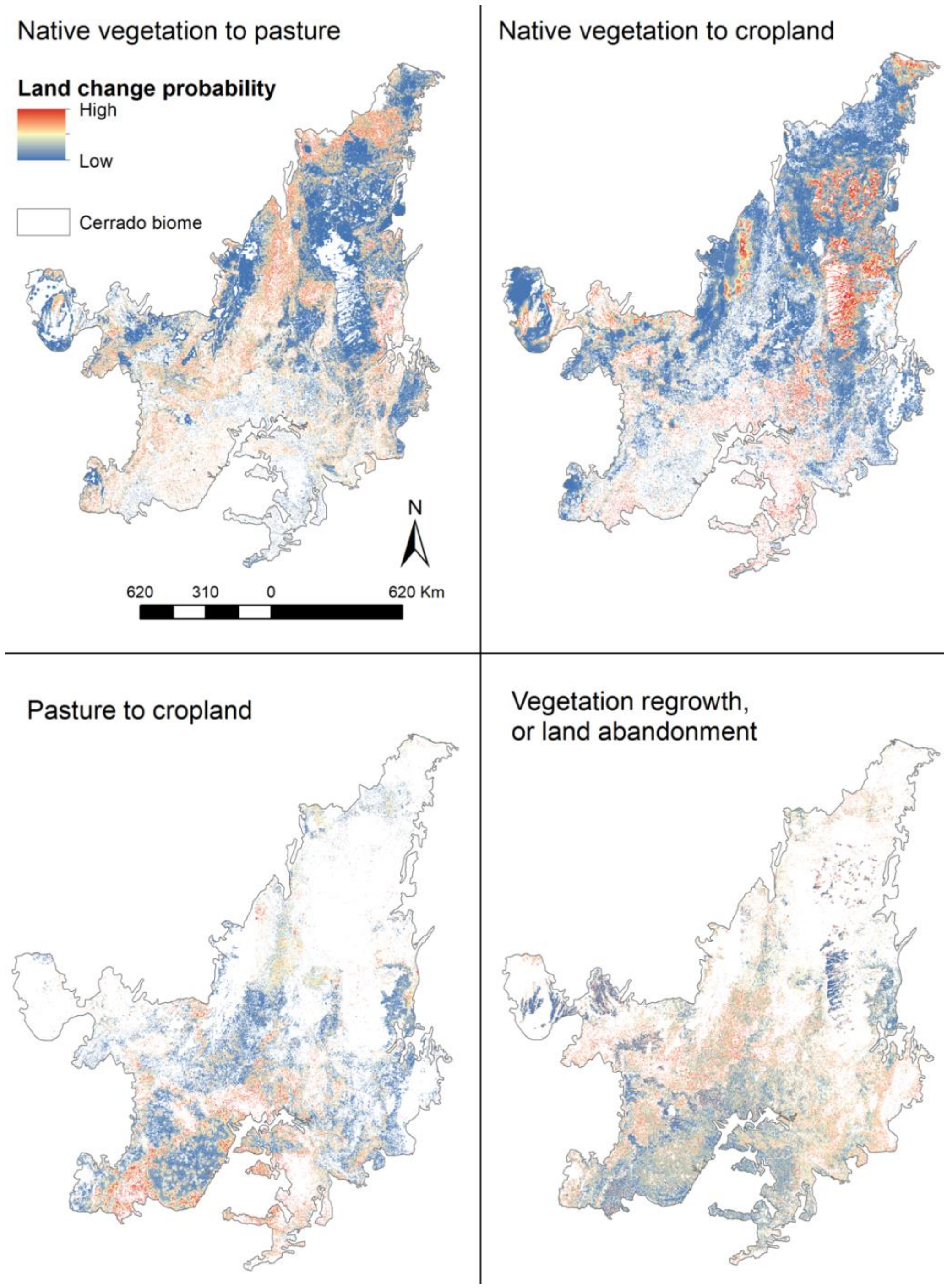

Figure 3.4: Probability of land change for 2046. Source: author's analysis in Dinamica EGO.

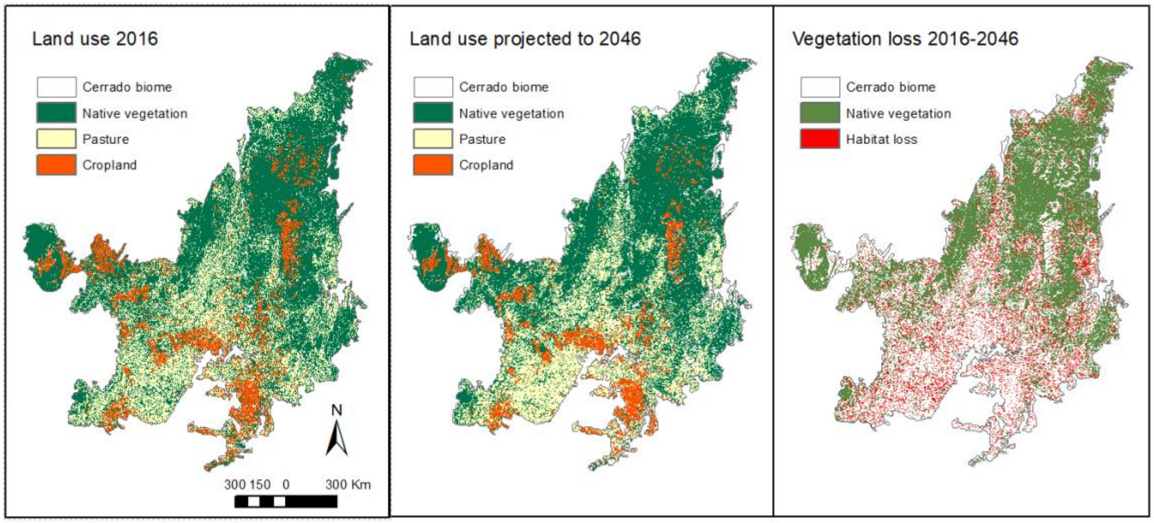

Figure 3.5: Land use (2016), land change simulation (2046) and projected vegetation loss (2016-2046). Source: Mapbiomas and author's analysis in Dinamica EGO.

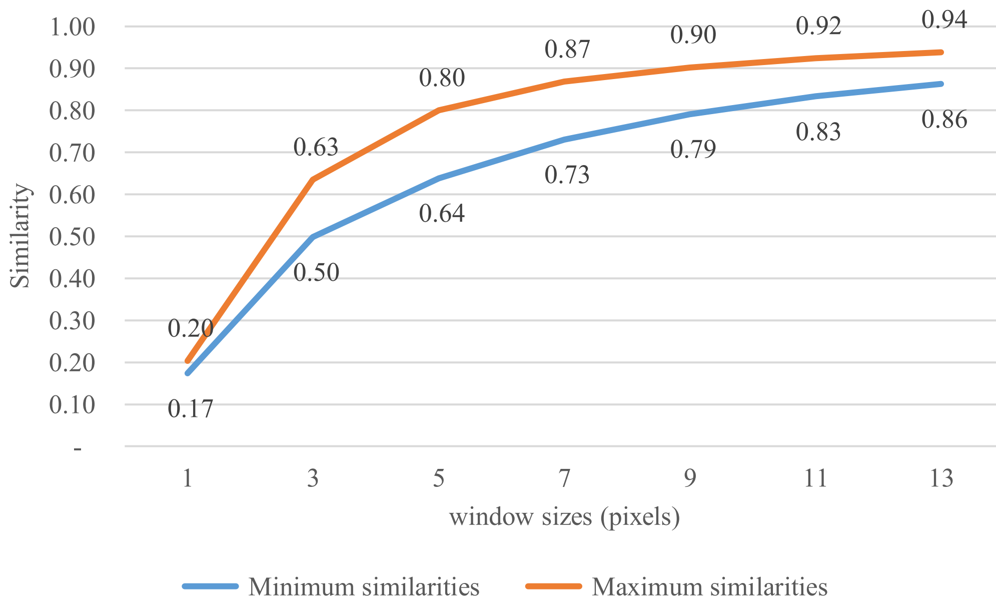

Figure 3.6: Similarity between land use simulation and current land use for Cerrado in 2016. Source: Author's analysis in Dinamica EGO.

Land change and climate scenarios

The projected increase in temperature by 2046 corresponds to the zones of higher probability of land change for pasture and cropland (figures 3 and 4), both in the north of the Cerrado biome. The projected farmland expansion in combination with increasing temperatures will shift the current distribution of agriculture to areas with higher temperature and risks (Figure 3.7). For example, in the range of 26-28 Celsius, I estimate additional 60,000 km^2 of crops and ~138,000 km^2 of pastures. As seen in the previous chapter, the increase in temperatures causes a reduction in agricultural productivity and induces land concentration. Soybean farming is the main activity affected, as it is the main driver of vegetation loss in agricultural frontiers (i.e., Matopiba and the State of Mato Grosso) since the 2000s and corresponds to half of the total agricultural production (IBGE, 2018a). Considering the extension and heterogeneity of temperature distribution in the Cerrado (Figure 3.3), the impact in agricultural productivity will not be equal for all the regions (Faria, 2012). Faria (2012) used a computable general equilibrium model to assess the effects of climate change on agricultural output of Brazil between 1996 and 2006 and found that temperature increases had an uneven impact on GDP at state level.

The expected increases in temperature will extend the drought periods in the Cerrado (Pires et al., 2016) and is likely to increase the demand for irrigation and put more pressure on surface and groundwater resources (Latrubesse et al., 2019). From 2000 to 2017, irrigated areas by central pivots grew by 182% (433,107ha to 1,222,409ha) in the Cerrado, according to the National Agency of Water (ANA & Embrapa, 2019). The expansion of pivots occurred mainly in the southeast region (states of Sao Paulo and Minas Gerais) and the state of Bahia (Matopiba region). If land change and temperature projections come to fruition in the future, it stands to reason that irrigated agriculture will continue to expand in the Cerrado. Nevertheless, rising temperatures also increase evaporation and reduce the availability of surface water for irrigation, requiring water management and more efficient irrigation technologies in the next decades.

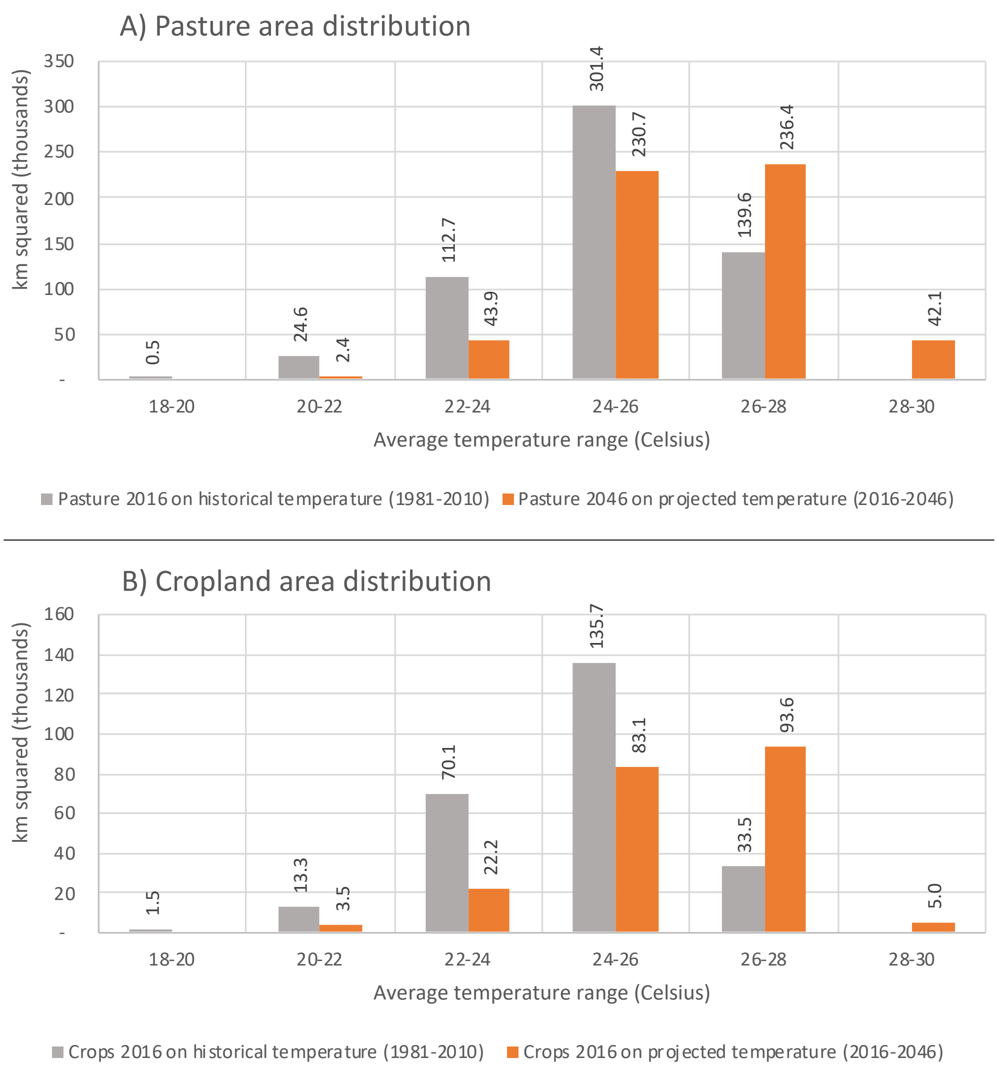

Figure 3.7: Distribution of agricultural area on current and projected land use and average temperature. Source: Author's analysis and INPE's temperature projections.

DISCUSSION

The Cerrado biome is a global hotspot for biodiversity conservation (Myers et al., 2000; Mittermeier et al., 2011), the second largest biome in South America, and have lost almost half of its native vegetation for agriculture since the 1980s. However, recent farmland expansion tends to occupy marginal lands where temperature is projected to increase in the next few decades. According to my estimates, at least 60 thousand km^2 of cropland and 138 thousand km^2 of pastures will be created in places with projected higher annual temperatures. Most of Cerrado croplands are occupied by soybeans, which can suffer a reduction of 4% for each 1°C increase in temperature, according to the estimates shown in Chapter 2. The results indicate the need for land management policies, from government and private sector to mitigate the negative effects of rising temperatures in the Cerrado biome. Is it worth continuing this expansion under such a scenario where risks from crop losses are likely to increase? To avoid such scenario, I suggest a combination of conservation policies, compensation for avoided land clearing, and agricultural intensification.

The creation of Protected Areas is the main strategy to halt farmland expansion over areas with increasing climatic risk for crop yield and important to ecosystem services. According to my land change model, Protected Areas lower the probability of vegetation loss in all subregions, but the status of protection remains fragile. For instance, Protected Areas cover ~8% of Cerrado, in comparison to 46% of the Amazon (Brasil, 2019). Most of the Cerrado lands are already under the private ownership domain (~85% of total area, including 49Mha of native vegetation, according to the Brazilian Rural Environmental Registry), with little public lands left for the creation of new protected areas (MMA, n.d.). Thus, engagement and participation of private landowners will be crucial for the protection of the remaining Cerrado vegetation. The problem may be the effectiveness for biodiversity conservation and ecosystem services/functions.

Thus, a complementary approach is to pay landowners to avoid clearing vegetation in private areas, based on the opportunity cost of the land or acquisition of private properties for conservation purposes such as the approach used by The Nature Conservancy in many places (Gerber & Rissman, 2012). Most of the cropland expansion in the Matopiba is related to local farmers' investments, and strong support of traders (i.e., technical assistance and contract of future purchase). Hence, considering land prices (FNP, 2018) as a proxy for expected gains of land use, I estimate that an incentive of BRL 12,750/ha for pastureland and BRL 31,438/ha for cropland would reduce 90% of vegetation loss up to 2046 (Figure 3.8)[2]. According to the Brazilian law, the legal instrument for permanent protection of these areas would be the creation of a Private Reserves of Natural Heritage (RRPN, in Portuguese acronym). However, a private agreement could be made to offset emissions from a third party or create carbon credits. In this case, the incentive could be paid in annual amounts, at a discount rate of 3 to 7%, or BRL 382 to 892/ha/year for pastures and BRL 912 to 2,129/ha/year for cropland. The definition of the discount rate is based on interviews with producers (Chapter 2) and their answers about willingness to receive compensation for not clearing vegetation; these rates also reflect similar values from the literature (Latawiec et al., 2017).

[2] This is a supplementary analysis to the discussion. As it strays from the core of this chapter, the methodological procedures and data set description are available in the Appendix.

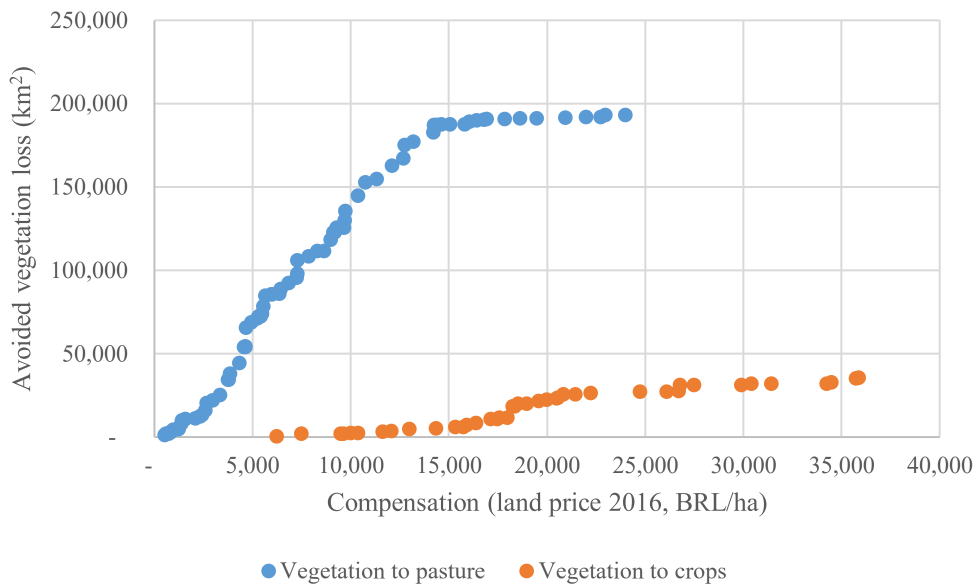

Figure 3.8: Avoided land clearing by compensation. Land prices in 2016 values. Source: elaborated with data from FNP (2018) and land change modeling.

Although my results are consistent with recent data and literature of land use change in the Cerrado, it has caveats. First, the Cerrado has a wide socioeconomic and environmental heterogeneity within the biome. Therefore, general models always require a downscaling to understand how land change dynamics take place in the context of local governance. Also, the purpose of this chapter was to model the spatial pattern and not the process (i.e., WoE coefficients do not represent the partial effect of the variables). Second, land change models are stationary, and different land uses may have different drivers. Nonetheless, my model was able to identify the vegetation loss and regrowth patterns using the best land cover data available. In this study however, I did not assess possible changes in the underlying causes, such as political contexts or how pandemic scenarios affected institutions, land policies, and peoples' decisions about land use. For instance, private sector commitments to halt deforestation (i.e., soy moratorium) that are now in place in the Amazon could be expanded to the Cerrado in order to avoid leakage and increase its overall effectiveness (Garrett et al., 2019). Finally, the creation of Protected Areas has limitations due to lack of availability of public lands, and private instruments to compensate avoided deforestation still lacks a legal framework and regulation.

In conclusion, the trend of land change in the Cerrado combined with scenarios of rising temperatures that reduce productivity and increase the dependence on irrigation technology is troublesome. This scenario can be avoided or mitigated by land policies and private agreements, such as creation of PA, expansion of soy moratorium, and a financial mechanism to compensate avoided land clearing in private properties. According to the modeling, regrowth is a strong trend in land change, maybe due to land clearing in non-suitable areas for agriculture. Therefore, public policies can guide the restoration and incentivize the recovery of cleared areas, particularly those that are important for water resources and ecosystem functions such as riparian forests and around natural springs. For the consolidated areas of agriculture, sustainable intensification strategies may mitigate the risks of increasing temperatures. For instance, cropland expansion over pastures and livestock intensification in regions less vulnerable to droughts and average temperature changes. In fact, the expansion of crops over pastures has happened in the southeast and central region of Cerrado, with increasing livestock productivity due the reduction of available lands to convert and more profitable conditions (i.e., better infrastructure, proximity to central markets and ports). This could be scaleup through landscape planning, with public policies and market incentives. A combination of enforcement and conservation policies is necessary to mitigate the risk of land clearing leakage and rebound effect - when the intensification stimulates expansion in other areas due to increased profits.

Chapter 4: Conclusion

Since 1970s the occupation of Brazilian savannas has received several government incentives (i.e., public credit, construction of roads, research and development investments). In combination with strong demand for agricultural commodities from the international market (e.g., soybean), this region experienced drastic land changes in the past 50 years. However, recent farmland expansion on cheaper marginal lands of the Matopiba region has exposed farmers to economic shocks due to frequent droughts and above normal temperatures. In Chapter 2, I estimated that each 1°C increase in temperature was associated with a reduction of 4-17% in soybean yield, using data for the Cerrado region since 1980. During the 2015 drought, one of the most severe in the past few decades, productivity was 33% below the normal average crop productivity, with greater intensity in the ecotone between the Cerrado and the semi-arid biome (Matopiba region). Assuming that political and economic incentives that drove the expansion of croplands in the Cerrado in the past will remain in place, the land change modeling of Chapter 3 indicates that 198,000 km2 of farmland expansion may occur in areas vulnerable to drought until 2046. To mitigate the impacts and avoid a worst-case scenario, I suggest a combination of conservation policies (i.e., PAs), compensation for avoided land clearing, and incentives for adoption of sustainable intensification strategies.

Despite the negative effects of higher temperatures on crop yields, farmers believe these are the result of short-term fluctuations in the weather. For most respondents of my survey with farmers in the Matopiba (n = 90), the variations in temperature and rainfall are cyclical and the expected productivity is often believed to be result of modern inputs and good agricultural practices. Also, according to interviewed farmers, adaptations to and consequences of the extreme drought in 2015/2016 include switching to more drought tolerant crops, land concentration, and capital dependency in the form of investments in irrigation. As suggested by previous studies, climate change adaptation strategies may include land use change and even land abandonment (Laue & Arima, 2016; Deschênes & Greenstone, 2007), with social costs and consequences throughout the commodities' supply chains (Burke et al., 2015). According to the modeling in Chapter 3, regrowth of natural vegetation, often associated with land abandonment, is a strong trend in land change, maybe due to land clearing in non-suitable areas for agriculture. This indicates the necessity to better assess the risks and expectations of gains from agricultural expansion in certain regions vulnerable to rainfall shortage and water availability.

Farmers also expressed belief in technological innovation. However, based on observations from recent history, agricultural technologies do not provide adaptation to extreme heat (Schlenker & Roberts, 2009). Those technologies also created dependency on capital availability in the form of expensive investments, such as irrigation. Due to long dry periods that extends 4 to 6 months in the Cerrado, more than one million hectares are now irrigated by central pivots that rely both on surface and groundwater (ANA & Embrapa, 2019). The expected increases in temperature will extend the drought periods (Pires et al., 2016) and the demand for irrigation, and will put more pressure on water supplies (Latrubesse et al., 2019). Climate change might also negatively affect the practice of double cropping, a strategy of planting two crops, one after another, during the rainy season that is critical for the high productivity and profitability observed in the region. Double cropping may not fit into this shorter rainy season if climate change predictions come into fruition. For irrigated areas, this dependence on central pivot is already the source of local conflicts and water shortages in urban areas (Maneta et al., 2009; Pousa et al., 2019). In the scenario of increasing demand for water resources, public policies need to be enforced to provide sustainable water management. In the scenario of increasing demand for water resources, the water supply management will require robust regulation policies from federal and local governments, such as improvements in the irrigation licensing system. This topic was not explored in depth in the thesis but is worth future investigation.

The negative impact of higher temperatures on yields in new agricultural areas can be mitigated by land policies and production strategies, such as water management regulation, the creation of PAs, adoption of sustainable intensification, and the payment for avoided clearing in private lands. First, designating public lands as PAs might be an effective strategy to halt farmland expansion over marginal lands, and contribute to biodiversity conservation and ecosystem services in a region that is under protected when compared to the Amazon. Despite being a hotspot for conservation, the Cerrado has only 8% of its extent set as protected area. Second, paying landowners for avoiding land clearing within their lands could compensate them for the foregone profits and create ecological corridors in the landscape to protect riparian forests, wetlands, water springs, rivers, and biodiversity. I estimate that an incentive of BRL 12,750/ha for pastureland and BRL 31,438/ha for cropland would reduce 90% of vegetation loss up to 2046. This payment could be done in full, equivalent to purchasing land for conservation, or in annual stipends that would range from BRL 382 to 2,129/ha/year depending on the land use, location, and risk of land change. Finally, the adoption of sustainable intensification strategies (e.g., increasing the cattle stocking to release land to crops) would help the Brazilian agricultural sector to meet the growing international demand for commodities without expanding over areas vulnerable droughts. Furthermore, public policies can incentivize the restoration of cleared areas without agricultural suitability or areas that are important for water resources and ecosystem functions, such as riparian buffer zones around springs and rivers.

Agricultural adaptation still needs to be further studied within the local context, mainly due to the social impacts of weather extreme events. For example, my survey in the Matopiba indicated a likely trend towards land concentration and indebtedness by farmers due to drought shocks. However, due to the scope of this study, I have not deepened the understanding of the impacts on vulnerable populations and whoever gains or loses with current policies of financial relief to farmers. The solutions proposed in the discussion of my results are mostly based on neoliberal perspectives of market-based policies, under the assumption that financial incentives will protect the environment and economic efficiency will spare land and natural resources. In most cases, this only reflects top-down policies that ignore local social structures in favor of commodifying environmental services (Liverman & Vilas, 2006; Shapiro-Garza, 2013). In fact, further research is needed on the role of institutions, land market, and the potential changes in the food systems. For instance, few studies on land change address competitive land uses because farmland expansion has multidimensional aspects related to preferences for environmental conservation, expected financial gains within a context of public policies. Future research that combines game theory with behavioral theory could be a fruitful venue to describe in depth the decision-making process of farmland investments and how the ecological responses to climate change affect farmer's investments.

Appendices

SURVEY QUESTIONS WITH SOYBEAN FARMERS IN THE MATOPIBA REGION

The questionnaire below was conducted in 2017, in Portuguese, with farmers in the Matopiba region, Brazil. During this period, I was part of the IPAM (Acronym for Amazon Institute of Environmental Research) research team, where I coordinated the design and analysis of this research. They generously consent the use of this data set for academic purposes. It was never published before.

Questionário da pesquisa Matopiba

Número do questionário (ID do ponto GPS): __________

Entrevistador: ____________

Módulo 1: O produtor

1. Município: ___________________
2. Função do entrevistado: ( ) Dono ( ) Funcionário ( ) Gerente ( ) Outros
3. A área de plantio é: ( ) Arrendada ( ) Própria
4. ( ) Produtor individual ( ) Empresa/PJ
5. Você faz parte de alguma associação de produtores/cooperativas?

( ) Sim ( ) Não

6. Produção certificada? ( ) Sim ( ) Não

a. Se sim, qual? ______________

7. A propriedade possui Cadastro Ambiental Rural (CAR)? ( ) Sim ( ) Não
8. Tem imóvel com certificado na base do Incra? ( ) Sim ( ) Não

9. A propriedade é a principal fonte de renda? ( ) Sim ( ) Não

Módulo 2: Característica do imóvel e modo produção

10. Qual a área total da propriedade: ________

Área de uso agrícola (ha): ________

Área de pasto (ha): _____________

Área de RL (ha): __________

Área de APP (ha): __________

11. Ano de compra do imóvel? _____________

12. Ano de início da produção? _____________

13. Textura do solo em uma proporção entre arenoso e argiloso (soma de 100%):

a. Argiloso: __________ Arenoso: ___________

14. Quando começou o plantio da última safra (dia/mês/ano): ____________

15. Quando terminou o plantio da última safra (dia/mês/ano): ____________

16. Houve atraso no plantio? ( ) Não ( ) Sim. Motivo: __________

17. Houve replantio? ( ) Não ( ) Sim, quantas vezes: ________

18. Quais as variedades de sementes: ( ) convencional ( ) transgênico

a. Produtividade da variedade transgênica (sc./hectare): ___________

b. Produtividade da variedade convencional (sc./hectare): ___________

19. Grupo de maturação (ciclo da soja): ______________

20. Utiliza os produtos abaixo (marcar mais de um, se for o caso):

Fungicida ( ) | Herbicida ( ) | Inseticida ( )

a. Qual a frequência de aplicação de cada produto

21. Quando começou a colheita do último ano (dia/mês/ano): ____________

22. Quando terminou a colheita do ultimo ano (dia/mês/ano): ____________

23. Houve atraso na colheita? ( ) Não ( ) Sim. Motivo: ___________

24. Causas da perda de produtividade: _________________________

25. Tem vegetação nativa na fazenda? ( ) Sim ( ) Não

26. Por que você mantém a vegetação na sua fazenda:

( ) Não desvalorizar a propriedade

( ) Risco de multa/embargo

( ) Acesso a mercado ( ) Acesso a crédito

( ) Cumprir lei

( ) Outros:_________

27. Tem vegetação nativa no entorno dos corpos d'água?

( ) Sim ( ) Não ( ) Não há rios ou corpos d'agua na propriedade

28. Qual a produtividade média da área agrícola (sacas/hectare), nas últimas quatro safras:

a. Safra 2012/2013: _________

b. Safra 2013/2014: _________

c. Safra 2014/2015: _________

d. Safra 2015/2016: _________

29. Faz safrinha (segunda safra no ano)? ( ) Não ( ) Sim. Qual: _____________

Modulo 2.1. Sobre a safrinha

1. Quando começou o plantio do último ano (dia/mês/ano): ____________
2. Quando terminou o plantio do último ano (dia/mês/ano): ____________
3. Houve replantio? ( ) Não ( ) Sim, quantas vezes: ________
4. Houve atraso no plantio? ( ) Não ( ) Sim. Motivo: __________
5. Utiliza os produtos abaixo (marcar mais de um, se for o caso):
   Fungicida ( ) | Herbicida ( ) | Inseticida ( )
   a. Qual a frequência de aplicação:
6. Fungicida: ________ | Herbicida: ________ | Inseticida:__________
7. Quando começou a colheita do último ano (dia/mês/ano): ____________
8. Quando terminou a colheita do ultimo ano (dia/mês/ano): ____________
9. Houve atraso na colheita? ( ) Não ( ) Sim. Motivo: __________
10. Quais as variedades de sementes: ( ) convencional ( ) transgênico
    a. Produtividade da variedade transgênica (sc./hectare): ___________
    b. Produtividade da variedade convencional (sc./hectare): ___________

30. Você adota integração lavoura-pecuária?

( ) Não ( ) Não, mas pretendo ( ) Sim, adoto. Por quê?: ____________

31. Utiliza irrigação? ( ) Sim ( ) Não

32. A data de plantio e colheita tem mudado nos últimos anos? ( ) Sim ( ) Não

a. Em quanto tempo? (dias) _____________

33. Quais os seguintes custos de produção (média):

Grupo	Item de despesas e custos	Valores médios (R$)
Insumos	Preço da tonelada de calcário (R$/ton)	
	Preço do frete do calcário (R$/ton)	
	Custo do adubo nitrogenado (NPK) (R$/ton)	
Mão de obra	Custo com funcionário fixo (média de R$/ mês)	
	Mão de obra variável (R$/diária)	
	Número de funcionários fixos (unid./ano)	
	Número de diaristas (unid./ano)	
Máquinas e capital	Arrendamento (R$/hectare/ano)	
	Aluguel de máquinas (R$/hora)	

Módulo 3: Gargalos financeiros e técnicos

34. Qual é a principal dificuldade para produzir na região? (deixar falar abertamente; marcar mais de um se for o caso)

( ) Assistência técnica ( ) Maior informação ( ) Crédito

( ) Maior relação com o poder público ( ) Tecnologia

( ) Mão de obra qualificada ( ) Outro

35. Nos últimos 5 anos você já acessou algum tipo de crédito para sua propriedade? ( ) Sim ( ) Não. Origem (bancos ou traders): ______________________

36. Há dificuldades para você acessar o crédito rural? ( ) Não ( ) Sim. Quais (ex.: sem regularização fundiária, demora na liberação do recurso, etc): _________

37. Atualmente, a propriedade conta com acompanhamento de assistência técnica? ( ) Sim ( ) Não

38. Qual a origem da assistência técnica? ( ) Pública ( ) Privada, paga pelo produtor ( ) Privada, paga por empresas (ex.: vendedor de sementes, traders, etc.).

Modulo 4: Sobre a vegetação nativa na fazenda

39. Você acha que a vegetação nativa traz benefícios para a sua fazenda?

( ) Sim ( ) Não. Quais? ___________________________________

40. Por qual valor mínimo estaria disposto a manter mais Reserva Legal do que o Código Florestal pede:

( ) O equivalente a uma saca de soja por hectare preservado

( ) Até 4 sacas/hectare

( ) Até 7 sacas/hectare

( ) Outro valor: ________

( ) Não sabe

( ) Nenhum valor. Não preservaria além do requerido pela lei.

41. Você adota alguma prática para manutenção/proteção da Reserva Legal?

( ) Sim ( ) Não

Módulo 5: Influência do clima na produção e adaptação

(deixar falar abertamente em todas)

42. Percebe alteração no regime de chuvas na região? ( ) Não ( ) Sim, como e desde quando?

43. Percebe alteração na temperatura nesta região? ( ) Não ( ) Sim, como e desde quando?

44. Se a resposta foi sim para as duas perguntas anteriores, responder a esta questão, se a resposta for não, pular para a próxima.

a. Na sua opinião, quais fatores têm afetado o clima?

45. Você toma alguma medida para reduzir os efeitos da falta ou excesso de chuva ou temperaturas elevadas na sua produção? ( ) Não ( ) Sim

a. Quais medidas: ___________________________________

SIMILARITY OF ALTERNATIVE LAND CHANGE MODELS

Window sizes	Minimum similarities	Maximum similarities
1	0.08	0.50
3	0.19	0.80
5	0.33	0.90
7	0.45	0.93
9	0.54	0.94
11	0.61	0.95
13	0.67	0.95

Table A.1: Similarity between land use simulation and current land use for Cerrado in 2016, without subregional models.

Window sizes	**Minimum similarities**	**Maximum similarities**
1	0.09	0.48
3	0.24	0.77
5	0.39	0.88
7	0.51	0.92
9	0.60	0.94
11	0.67	0.95
13	0.71	0.96

Table A.2: Similarity between land use simulation and current land use for Cerrado in 2016, with subregions at municipal level.

LAND PRICES IN THE CERRADO BIOME

To test the relationship between land change and prices I collected the average land prices information (BRL/hectare) to pastures and crops from FNP's annual reports (FNP, 2018). These values are available by groups of municipalities in Brazil, then I applied an areal interpolation to make it possible the cross the prices with the land change rasters. I had access to land prices for the period of 2001-2016. The area of avoided land clearing (Figure 3.8) is cumulative up to a correspondent land price.

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